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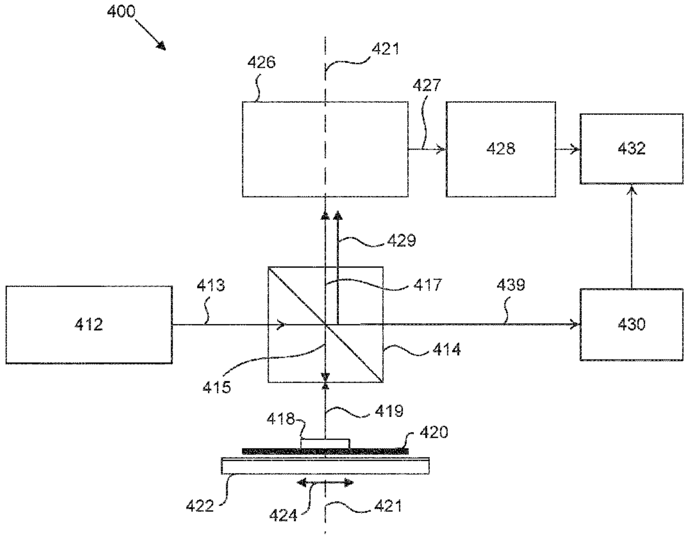

FIG. 4A

(57) **Abstract:** A lithographic apparatus includes a projection system and an inspection system that includes a radiation system, a photonic integrated circuit system, and a detector system. The projection system projects an image of a patterning device onto a substrate. The radiation system directs radiation toward a target on the substrate to generate scattered radiation from the target. The radiation system includes a radiation source to generate radiation and an optical system to focus the radiation on the target. The photonic integrated circuit system includes a waveguide system integrated on a board and a radiation coupler disposed at a waveguide of the waveguide system. The radiation coupler launches at least a portion of the scattered radiation into the waveguide system. The detector system receives the scattered radiation from the waveguide system and generates a measurement signal based on the scattered radiation.

*[Continued on next page]*

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# A LITHOGRAPHIC APPARATUS AND INSPECTION SYSTEM WITH HYBRID FREE SPACE OPTICS AND PHOTONIC INTEGRATED CIRCUITS

## CROSS REFERENCE TO RELATED APPLICATION

**[0001]** This application claims priority to U.S. Application No. 63/506,466, filed June 6, 2023, and which is incorporated herein in its entirety by reference.

## FIELD

**[0002]** The present disclosure relates to metrology systems, for example, an alignment sensor for monitoring fabrication processes in lithographic apparatuses and systems.

## BACKGROUND

**[0003]** A lithographic apparatus is a machine that applies a desired pattern onto a substrate, usually onto a target portion of the substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In that instance, a patterning device, which can be a mask or a reticle, can be used to generate a circuit pattern to be formed on an individual layer of the IC. This pattern can be transferred onto a target portion (e.g., comprising part of, one, or several dies) on a substrate (e.g., a silicon wafer). Transfer of the pattern is typically via imaging onto a layer of radiation-sensitive material (photoresist or simply "resist") provided on the substrate. In general, a single substrate will contain a network of adjacent target portions that are successively patterned. Known lithographic apparatuses include so-called steppers, in which each target portion is irradiated by exposing an entire pattern onto the target portion at one time, and so-called scanners, in which each target portion is irradiated by scanning the pattern through a radiation beam in a given direction (the "scanning"-direction) while synchronously scanning the target portions parallel or anti-parallel to this scanning direction. It is also possible to transfer the pattern from the patterning device to the substrate by imprinting the pattern onto the substrate.

**[0004]** During lithographic operation, different processing steps can entail different layers to be sequentially formed on the substrate. Accordingly, it can be necessary to position the substrate relative to prior patterns formed thereon with a high degree of accuracy. Generally, alignment marks are placed on the substrate to be aligned and are located with reference to a second object. A lithographic apparatus can use an alignment apparatus for detecting positions of the alignment marks and for aligning the substrate using the alignment marks to ensure accurate exposure from a mask. Misalignment between the alignment marks at two different layers is measured as overlay error.

**[0005]** In order to monitor the lithographic process, parameters of the patterned substrate are measured. Parameters can include, for example, the overlay error between successive layers formed in or on the patterned substrate and critical linewidth of developed photosensitive resist. This measurement can be performed on a product substrate and/or on a dedicated metrology target. There are various techniques for making measurements of the microscopic structures formed in lithographic processes, including the use of scanning electron microscopes and various specialized tools. A fast and non-invasive form of a specialized inspection tool is a scatterometer in which a beam of radiation is directed onto a target on the surface of the substrate and properties of the scattered or reflected beam are measured. By comparing the properties of the beam before and after it has been reflected or scattered by the substrate, the properties of the substrate can be determined. This can be done, for example, by comparing the reflected beam with data stored in a library of known measurements associated with known substrate properties. Spectroscopic scatterometers direct a broadband radiation beam onto the substrate and measure the spectrum (intensity as a function of wavelength) of the radiation scattered into a particular narrow angular range. By contrast, angularly resolved scatterometers use a monochromatic radiation beam and measure the intensity of the scattered radiation as a function of angle.

**[0006]** Such optical scatterometers can be used to measure parameters, such as critical dimensions of developed photosensitive resist or overlay error (OV) between two layers formed in or on the patterned substrate. Properties of the substrate can be determined by comparing the properties of an illumination beam before and after the beam has been reflected or scattered by the substrate.

**[0007]** A lithographic system can output only a finite number of fabricated devices in a given timeframe. Performing faster metrology can increase fabrication speeds. One method to improve measurement speeds is to implement multiple sensors for mitigating the travel time of a single sensor having to move from mark to mark to perform measurements. Due to size constraints, conventional sensors with free-space optical components (such as lenses, filters, mirrors, or the like) can be large and not very convenient for scalable implementation. On the other hand, a small sensor can be designed by implementing photonic integrated circuit technology, but such sensors can be challenging to implement when sourcing multiple wavelengths.

## SUMMARY

**[0008]** Accordingly, it is desirable to have multi-wavelength capability of free-space optics for sourcing radiation as well as the miniaturization capabilities of photonic integrate circuit components responsible for collection of scattered radiation from a mark. Optical inspection processes can be performed faster based on aspects described herein.

**[0009]** In some aspects, a lithographic apparatus comprises a projection system, an inspection system, and a detector system. The projection system is configured to project an image of a patterning device onto a substrate. The radiation system is configured to direct radiation toward a target on the substrate to generate scattered radiation from the target. The radiation system comprises a radiation source configured to generate the radiation and an optical system configured to focus the radiation on the target. The photonic integrated circuit system is configured to receive the scattered radiation from the target. The photonic integrated circuit system comprises a waveguide system integrated on a board and a radiation coupler disposed at a waveguide of the waveguide system. The radiation coupler is configured to launch at least a portion of the scattered radiation into the waveguide system. The detector system is configured to receive the scattered radiation from the waveguide system and to generate a measurement signal based on the scattered radiation.

**[0010]** In some aspects, an inspection system comprises a radiation system, a photonic integrated circuit system, and a detector system. The detector system is configured to direct radiation toward a target to generate scattered radiation from the target. The radiation system comprises a radiation source and an optical system. The radiation source is configured to generate the radiation. The optical system is configured to focus the radiation on the target. The photonic integrated circuit system is configured to receive the scattered radiation from the target. The photonic integrated circuit system comprises a waveguide system integrated on a board and a radiation coupler disposed on a waveguide of the waveguide system. The radiation coupler is configured to launch at least a portion of the scattered radiation into the waveguide system. The detector system is configured to receive the scattered radiation from the waveguide system and to generate a measurement signal based on the scattered radiation.

**[0011]** In some aspects, an inspection system comprises an optical system and a photonic integrated circuit system. The optical system is configured to focus radiation on a target to generate scattered radiation. The optical system comprises a first adjustable lens support, a second adjustable lens support, and an adjustable fiber connector. The first adjustable lens support is configured to adjust an optical alignment of a first lens. The second adjustable lens support is configured to adjust an optical alignment of a second lens. The adjustable fiber connector is configured to direct a beam from an optical fiber to the optical system and to adjust a position of the optical fiber to align the beam along an optical axis of the optical system. The photonic integrated circuit system is configured to receive the scattered radiation from the target. The photonic integrated circuit system comprises a waveguide system integrated on a board and radiation coupler disposed at a waveguide of the waveguide system. The radiation coupler is configured to launch the scattered radiation into the waveguide system. The waveguide system is configured to guide the scattered radiation to a detector system.

**[0012]** Further features of various aspects of the present disclosure are described in detail below with reference to the accompanying drawings. It is noted that the present disclosure is not limited to the specific aspects described herein. Such aspects are presented herein for illustrative purposes only. Additional aspects will be apparent to those skilled in the relevant art(s) based on the teachings contained herein.

## BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

**[0013]** The accompanying drawings, which are incorporated herein and form part of the specification, illustrate the present disclosure and, together with the description, further serve to explain the principles of the present disclosure and to enable those skilled in the relevant art(s) to make and use aspects described herein.

**[0014]** FIG. 1A shows a reflective lithographic apparatus, according to some aspects.

**[0015]** FIG. 1B shows a transmissive lithographic apparatus, according to some aspects.

**[0016]** FIG. 2 shows more details of a reflective lithographic apparatus, according to some aspects.

**[0017]** FIG. 3 shows a lithographic cell, according to some aspects.

**[0018]** FIGS. 4A, 4B, 5, 6, 7A, and 7B show inspection systems, according to some aspects.

**[0019]** FIG. 8 shows a photonic integrated circuit system, according to some aspects.

**[0020]** The features of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. Additionally, generally, the left-most digit(s) of a reference number identifies the drawing in which the reference number first appears. Unless otherwise indicated, the drawings provided throughout the disclosure should not be interpreted as to-scale drawings.

## DETAILED DESCRIPTION

**[0021]** The aspects described herein, and references in the specification to "one aspect," "an aspect," "an exemplary aspect," "an example aspect," etc., indicate that the aspects described can include a particular feature, structure, or characteristic, but every aspect may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same aspect. Further, when a particular feature, structure, or characteristic is described in connection with an aspect, it is understood that it is within the knowledge of those skilled in the art to effect such feature, structure, or characteristic in connection with other aspects whether or not explicitly described.

**[0022]** Spatially relative terms, such as "beneath," "below," "lower," "above," "on," "upper" and the like, can be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus can be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein can likewise be interpreted accordingly.

**[0023]** The terms "about," "approximately," or the like can be used herein to indicate the value of a given quantity that can vary based on a particular technology. Based on the particular technology, the terms "about," "approximately," or the like can indicate a value of a given quantity that varies within, for example, 10–30% of the value (e.g., ±10%, ±20%, or ±30% of the value).

**[0024]** Enumerative adjectives (e.g., "first," "second," "third," or the like) can be used to distinguishing like elements without establishing an order, hierarchy, quantity, or permanent numeric assignment (unless otherwise noted). For example, the terms "first target" and "second target" can be used in a manner analogous to "$i^{th}$ target" and "$j^{th}$ target" so as to facilitate the distinguishing of two targets without specifying a particular order, hierarchy, quantity, or immutable numeric correspondence.

**[0025]** Aspects of the present disclosure can be implemented in hardware, firmware, software, or any combination thereof. Aspects of the disclosure can also be implemented as instructions stored on a computer-readable medium, which can be read and executed by one or more processors. A machine-readable medium can comprise any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computing device). For example, a machine-readable medium can comprise read only memory (ROM); random access memory (RAM); magnetic disk storage media; optical storage media; flash memory devices; electrical, optical, acoustical or other forms of propagated signals (e.g., carrier waves, infrared signals, digital signals, etc.), and others. Furthermore, firmware, software, routines, and/or instructions can be described herein as performing certain actions. However, it should be appreciated that such descriptions are merely for convenience and that such actions result from computing devices, processors, controllers, or other devices executing the firmware, software, routines, instructions, etc. The term “machine-readable medium” can be interchangeable with similar terms, for example, “computer program product,” “computer-readable medium,” “non-transitory computer-readable medium,” or the like. The term “non-transitory” can be used herein to characterize one or more forms of computer readable media except for a transitory, propagating signal.

**[0026]** Before describing such aspects in more detail, however, it is instructive to present an example environment in which aspects of the present disclosure can be implemented.

**[0027]** *Example Lithographic Systems*

**[0028]** FIGS. 1A and 1B show a lithographic apparatus 100 and a lithographic apparatus 100’, respectively, in which aspects of the present disclosure can be implemented. Lithographic apparatus 100 and lithographic apparatus 100’ each can comprise the following: an illumination system (illuminator) IL configured to condition a radiation beam B (for example, deep ultra violet or extreme ultra violet radiation); a support structure (for example, a mask table) MT configured to support a patterning device (for example, a mask, a reticle, or a dynamic patterning device) MA and connected to a first positioner PM configured to accurately position the patterning device MA; and, a substrate table (for example, a wafer table) WT configured to hold a substrate (for example, a resist coated wafer) W and connected to a second positioner PW configured to accurately position the substrate W. Lithographic apparatus 100 and 100’ also have a projection system PS configured to project a pattern imparted to the radiation beam B by patterning device MA onto a target portion (for example, comprising one or more dies) C of the substrate W. In lithographic apparatus 100, the patterning device MA and the projection system PS are reflective. In lithographic apparatus 100’, the patterning device MA and the projection system PS are transmissive.

**[0029]** The illumination system IL can comprise various types of optical components, such as refractive, reflective, catadioptric, magnetic, electromagnetic, electrostatic, or other types of optical components, or any combination thereof, for directing, shaping, or controlling the radiation beam B.

**[0030]** The support structure MT holds the patterning device MA in a manner that depends on the orientation of the patterning device MA with respect to a reference frame, the design of at least one of the lithographic apparatus 100 and 100', and other conditions, such as whether or not the patterning device MA is held in a vacuum environment. The support structure MT can use mechanical, vacuum, electrostatic, or other clamping techniques to hold the patterning device MA. The support structure MT can be a frame or a table, for example, which can be fixed or movable. By using sensors, the support structure MT can ensure that the patterning device MA is at a desired position, for example, with respect to the projection system PS.

**[0031]** The term "patterning device" MA should be broadly interpreted as referring to any device that can be used to impart a radiation beam B with a pattern in its cross-section, such as to create a pattern in the target portion C of the substrate W. The pattern imparted to the radiation beam B can correspond to a particular functional layer in a device being created in the target portion C to form an integrated circuit.

**[0032]** The patterning device MA can be transmissive (as in lithographic apparatus 100' of FIG. 1B) or reflective (as in lithographic apparatus 100 of FIG. 1A). Examples of patterning devices MA include reticles, masks, programmable mirror arrays, or programmable LCD panels. Masks are well known in lithography, and include mask types such as binary, alternating phase shift, or attenuated phase shift, as well as various hybrid mask types. An example of a programmable mirror array employs a matrix arrangement of small mirrors, each of which can be individually tilted so as to reflect an incoming radiation beam in different directions. The tilted mirrors impart a pattern in the radiation beam B, which is reflected by a matrix of small mirrors.

**[0033]** The term "projection system" PS can encompass any type of projection system, including refractive, reflective, catadioptric, magnetic, electromagnetic and electrostatic optical systems, or any combination thereof, as appropriate for the exposure radiation being used, or for other factors, such as the use of an immersion liquid on the substrate W or the use of a vacuum. A vacuum environment can be used for EUV or electron beam radiation since other gases can absorb too much radiation or electrons. A vacuum environment can therefore be provided to the whole beam path with the aid of a vacuum wall and vacuum pumps.

**[0034]** Lithographic apparatus 100 and/or lithographic apparatus 100' can be of a type having two (dual stage) or more substrate tables WT (and/or two or more mask tables). In such "multiple stage" machines, the additional substrate tables WT can be used in parallel, or preparatory steps can be carried out on one or more tables while one or more other substrate tables WT are being used for exposure. In some situations, the additional table may not be a substrate table WT.

**[0035]** The lithographic apparatus can also be of a type wherein at least a portion of the substrate can be covered by a liquid having a relatively high refractive index, e.g., water, so as to fill a space between the projection system and the substrate. An immersion liquid can also be applied to other spaces in the lithographic apparatus, for example, between the mask and the projection system. Immersion techniques are well known in the art for increasing the numerical aperture of projection systems. The term “immersion” as used herein does not mean that a structure, such as a substrate, must be submerged in liquid. For example, a liquid can be located between the projection system and the substrate during exposure.

**[0036]** Referring to FIGS. 1A and 1B, the illuminator IL receives a radiation beam from a radiation source SO. The source SO and the lithographic apparatus 100, 100’ can be separate physical entities, for example, when the source SO is an excimer laser. In such cases, the source SO is not considered to form part of the lithographic apparatus 100 or 100’, and the radiation beam B passes from the source SO to the illuminator IL with the aid of a beam delivery system BD (in FIG. 1B) including, for example, suitable directing mirrors and/or a beam expander. In other cases, the source SO can be an integral part of the lithographic apparatus 100, 100’, for example, when the source SO is a mercury lamp. A radiation system can comprise the source SO, the illuminator IL, and/or the beam delivery system BD.

**[0037]** The illuminator IL can comprise an adjuster AD (in FIG. 1B) for adjusting the angular intensity distribution of the radiation beam. Generally, at least the outer and/or inner radial extent (commonly referred to as “σ-outer” and “σ-inner,” respectively) of the intensity distribution in a pupil plane of the illuminator can be adjusted. In addition, the illuminator IL can comprise various other components (in FIG. 1B), such as an integrator IN and a condenser CO. The illuminator IL can be used to condition the radiation beam B to have a desired uniformity and intensity distribution in its cross section.

**[0038]** Referring to FIG. 1A, the radiation beam B is incident on the patterning device (for example, mask) MA, which is held on the support structure (for example, mask table) MT, and is patterned by the patterning device MA. In lithographic apparatus 100, the radiation beam B is reflected from the patterning device (for example, mask) MA. After being reflected from the patterning device (for example, mask) MA, the radiation beam B passes through the projection system PS, which focuses the radiation beam B onto a target portion C of the substrate W. With the aid of the second positioner PW and position sensor IF2 (for example, an interferometric device, linear encoder, or capacitive sensor), the substrate table WT can be moved accurately (for example, so as to position different target portions C in the path of the radiation beam B). Similarly, the first positioner PM and another position sensor IF1 can be used to accurately position the patterning device (for example, mask) MA with respect to the path of the radiation beam B. Patterning device (for example, mask) MA and substrate W can be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2.

**[0039]** Referring to FIG. 1B, the radiation beam B is incident on the patterning device (for example, mask MA), which is held on the support structure (for example, mask table MT), and is patterned by the patterning device. Having traversed the mask MA, the radiation beam B passes through the projection system PS, which focuses the beam onto a target portion C of the substrate W. The projection system has a pupil conjugate PPU to an illumination system pupil IPU. Portions of radiation emanate from the intensity distribution at the illumination system pupil IPU and traverse a mask pattern without being affected by diffraction at the mask pattern and create an image of the intensity distribution at the illumination system pupil IPU.

**[0040]** The projection system PS projects an image of the mask pattern MP, where the image is formed by diffracted beams produced from the mark pattern MP by radiation from the intensity distribution, onto a photoresist layer coated on the substrate W. For example, the mask pattern MP can comprise an array of lines and spaces. A diffraction of radiation at the array and different from zeroth order diffraction generates diverted diffracted beams with a change of direction in a direction perpendicular to the lines. Undiffracted beams (i.e., so-called zeroth order diffracted beams) traverse the pattern without any change in propagation direction. The zeroth order diffracted beams traverse an upper lens or upper lens group of the projection system PS, upstream of the pupil conjugate PPU of the projection system PS, to reach the pupil conjugate PPU. The portion of the intensity distribution in the plane of the pupil conjugate PPU and associated with the zeroth order diffracted beams is an image of the intensity distribution in the illumination system pupil IPU of the illumination system IL. The aperture device PD, for example, is disposed at or substantially at a plane that includes the pupil conjugate PPU of the projection system PS.

**[0041]** The projection system PS is arranged to capture (e.g., using a lens or lens group L) the zeroth order diffracted beams, first order diffracted beams, and/or higher order diffracted beams (not shown). In some aspects, dipole illumination for imaging line patterns extending in a direction perpendicular to a line can be used to utilize the resolution enhancement effect of dipole illumination. For example, first-order diffracted beams interfere with corresponding zeroth-order diffracted beams at the level of the wafer W to create an image of the line pattern MP at highest possible resolution and process window (i.e., usable depth of focus in combination with tolerable exposure dose deviations). In some aspects, astigmatism aberration can be reduced by providing radiation poles (not shown) in opposite quadrants of the illumination system pupil IPU. Further, in some aspects, astigmatism aberration can be reduced by blocking the zeroth order beams in the pupil conjugate PPU of the projection system associated with radiation poles in opposite quadrants. This is described in more detail in US 7,511,799 B2, issued Mar. 31, 2009, which is incorporated by reference herein in its entirety.

**[0042]** With the aid of the second positioner PW and position sensor IFD (for example, an interferometric device, linear encoder, or capacitive sensor), the substrate table WT can be moved accurately (for example, so as to position different target portions C in the path of the radiation beam B). Similarly, the first positioner PM and another position sensor (not shown in FIG. 1B) can be used to accurately position the mask MA with respect to the path of the radiation beam B (for example, after mechanical retrieval from a mask library or during a scan).

**[0043]** In general, movement of the mask table MT can be realized with the aid of a long-stroke module (coarse positioning) and a short-stroke module (fine positioning), which form part of the first positioner PM. Similarly, movement of the substrate table WT can be realized using a long-stroke module and a short-stroke module, which form part of the second positioner PW. In the case of a stepper (as opposed to a scanner), the mask table MT can be connected to a short-stroke actuator or can be fixed. Mask MA and substrate W can be aligned using mask alignment marks M1, M2, and substrate alignment marks P1, P2. Although the substrate alignment marks (as illustrated) occupy dedicated target portions, they can be located in spaces between target portions (known as scribe-lane alignment marks). Similarly, in situations in which more than one die is provided on the mask MA, the mask alignment marks can be located between the dies.

**[0044]** Mask table MT and patterning device MA can be in a vacuum chamber V, where an in-vacuum robot IVR can be used to move patterning devices such as a mask in and out of vacuum chamber. Alternatively, when mask table MT and patterning device MA are outside of the vacuum chamber, an out-of-vacuum robot can be used for various transportation operations, similar to the in-vacuum robot IVR. Both the in-vacuum and out-of-vacuum robots can be calibrated for a smooth transfer of any payload (e.g., mask) to a fixed kinematic mount of a transfer station.

**[0045]** The lithographic apparatus 100 and 100' can be used in at least one of the following modes:

**[0046]** 1. In step mode, the support structure (for example, mask table) MT and the substrate table WT are kept essentially stationary, while an entire pattern imparted to the radiation beam B is projected onto a target portion C at one time (i.e., a single static exposure). The substrate table WT is then shifted in the X and/or Y direction so that a different target portion C can be exposed.

**[0047]** 2. In scan mode, the support structure (for example, mask table) MT and the substrate table WT are scanned synchronously while a pattern imparted to the radiation beam B is projected onto a target portion C (i.e., a single dynamic exposure). The velocity and direction of the substrate table WT relative to the support structure (for example, mask table) MT can be determined by the (de-)magnification and image reversal characteristics of the projection system PS.

**[0048]** 3. In another mode, the support structure (for example, mask table) MT is kept substantially stationary holding a programmable patterning device, and the substrate table WT is moved or scanned while a pattern imparted to the radiation beam B is projected onto a target portion C. A pulsed radiation source SO can be employed and the programmable patterning device is updated as needed after each movement of the substrate table WT or in between successive radiation pulses during a scan. This mode of operation can be readily applied to maskless lithography that utilizes a programmable patterning device, such as a programmable mirror array.

**[0049]** Combinations and/or variations on the described modes of use or entirely different modes of use can also be employed.

**[0050]** In some aspects, lithographic apparatus 100 can comprise an extreme ultraviolet (EUV) source, which is configured to generate a beam of EUV radiation for EUV lithography. In general, the EUV source is configured in a radiation system, and a corresponding illumination system is configured to condition the EUV radiation beam of the EUV source.

**[0051]** In some aspects, lithographic apparatus 100' can comprise a deep ultraviolet (DUV) source, which is configured to generate a beam of DUV radiation for DUV lithography. In general, the DUV source is configured in a radiation system, and a corresponding illumination system is configured to condition the DUV radiation beam of the DUV source.

**[0052]** FIG. 2 shows the lithographic apparatus 100 in more detail, including the source collector apparatus SO, the illumination system IL, and the projection system PS. The source collector apparatus SO is constructed and arranged such that a vacuum environment can be maintained in an enclosing structure 220 of the source collector apparatus SO. An EUV radiation emitting plasma 210 can be formed by a discharge produced plasma source. EUV radiation can be produced by a gas or vapor, for example Xe gas, Li vapor, or Sn vapor in which EUV radiation emitting plasma 210 is created to emit radiation in the EUV range of the electromagnetic spectrum. The EUV radiation emitting plasma 210 is created by, for example, an electrical discharge causing at least a partially ionized plasma. Partial pressures of, for example, 10 Pa of Xe, Li, Sn vapor, or any other suitable gas or vapor can be used for efficient generation of the radiation. In some aspects, a plasma of excited tin (Sn) (e.g., excited via a laser) is provided to produce EUV radiation.

**[0053]** The radiation emitted by the EUV radiation emitting plasma 210 is passed from a source chamber 211 into a collector chamber 212 via an optional gas barrier or contaminant trap 230 (in some cases also referred to as contaminant barrier or foil trap), which is positioned in or behind an opening in source chamber 211. The contaminant trap 230 can comprise a channel structure. Contamination trap 230 can also comprise a gas barrier or a combination of a gas barrier and a channel structure. The contaminant trap or contaminant barrier 230 further indicated herein at least comprises a channel structure.

**[0054]** The collector chamber 212 can comprise a radiation collector CO, which can be a so-called grazing incidence collector. Radiation collector CO has an upstream radiation collector side 251 and a downstream radiation collector side 252. Radiation that traverses collector CO can be reflected off a grating spectral filter 240 to be focused in a virtual source point INTF. The virtual source point INTF is commonly referred to as the intermediate focus, and the source collector apparatus is arranged such that the intermediate focus INTF is located at or near an opening 219 in the enclosing structure 220. The virtual source point INTF is an image of the EUV radiation emitting plasma 210. Grating spectral filter 240 is used in particular for suppressing infra-red (IR) radiation.

**[0055]** Subsequently the radiation traverses the illumination system IL, which can include a faceted field mirror device 222 and a faceted pupil mirror device 224 arranged to provide a desired angular distribution of the radiation beam 221, at the patterning device MA, as well as a desired uniformity of radiation intensity at the patterning device MA. Upon reflection of the beam of radiation 221 at the patterning device MA, held by the support structure MT, a patterned beam 226 is formed and the patterned beam 226 is imaged by the projection system PS via reflective elements 228, 229 onto a substrate W held by the wafer stage or substrate table WT.

**[0056]** More elements than shown can generally be present in illumination optics unit IL and projection system PS. The grating spectral filter 240 can optionally be present, depending upon the type of lithographic apparatus. Further, there can be more mirrors present than those shown in the FIG. 2, for example there can be one to six additional reflective elements present in the projection system PS than shown in FIG. 2.

**[0057]** Collector optic CO, as illustrated in FIG. 2, is depicted as a nested collector with grazing incidence reflectors 253, 254, and 255, just as an example of a collector (or collector mirror). The grazing incidence reflectors 253, 254, and 255 are disposed axially symmetric around an optical axis O and a collector optic CO of this type is preferably used in combination with a discharge produced plasma source, often called a DPP source.

**[0058]** *Example Lithographic Cell*

**[0059]** FIG. 3 shows a lithographic cell 300, also sometimes referred to a lithocell or cluster, according to some aspects. Lithographic apparatus 100 or 100’ can form part of lithographic cell 300. Lithographic cell 300 can also comprise one or more apparatuses to perform pre- and post-exposure processes on a substrate. Conventionally these include spin coaters SC to deposit resist layers, developers DE to develop exposed resist, chill plates CH, and bake plates BK. A substrate handler, or robot, RO picks up substrates from input/output ports I/O1, I/O2, moves them between the different process apparatuses and delivers them to the loading bay LB of the lithographic apparatus 100 or 100’. These devices, which are often collectively referred to as the track, are under the control of a track control unit TCU, which is itself controlled by a supervisory control system SCS, which also controls the lithographic apparatus via lithography control unit LACU. Thus, the different apparatuses can be operated to maximize throughput and processing efficiency.

**[0060]** *Example Inspection System*

**[0061]** In order to control the lithographic process to place device features accurately on the substrate, alignment marks are generally provided on the substrate, and the lithographic apparatus comprises one or more inspection systems for accurate positioning of marks on a substrate. These alignment apparatuses are effectively position measuring apparatuses. Different types of marks and different types of alignment apparatuses and/or systems are known from different times and different manufacturers. A type of system widely used in current lithographic apparatus is based on a self-referencing interferometer as described in U.S. Patent No. 6,961,116 (den Boef *et al.*). Generally marks are measured separately to obtain X- and Y-positions. A combined X- and Y-measurement can be performed using the techniques described in U.S. Publication No. 2009/195768 A (Bijnen *et al.*), however. The full contents of both of these disclosures are incorporated herein by reference.

**[0062]** FIG. 4A shows a cross-sectional view of an inspection system 400 that can be implemented as a part of lithographic apparatus 100 or 100’, according to some aspects. In some aspects, inspection system 400 can be configured to align a substrate (e.g., substrate W) with respect to a patterning device (e.g., patterning device MA). Inspection system 400 can be further configured to detect positions of alignment marks on the substrate and to align the substrate with respect to the patterning device or other components of lithographic apparatus 100 or 100’ using the detected positions of the alignment marks.

Such alignment of the substrate can ensure accurate exposure of one or more patterns on the substrate.

**[0063]** The terms "inspection system," "metrology system," or the like can be used herein to refer to, e.g., a device used for measuring a property of a structure (e.g., overlay sensor, critical dimension sensor, or the like), a device or system used in a lithographic apparatus to inspect an alignment of a wafer (e.g., alignment sensor), or the like.

**[0064]** In some aspects, inspection system 400 can include an illumination system 412, a beam splitter 414, an interferometer 426, a detector 428, a beam analyzer 430, and a processor 432. Illumination system 412 can be configured to provide an electromagnetic narrow band radiation beam 413 having one or more passbands. In an example, the one or more passbands can be within a spectrum of wavelengths between about 500 nm to about 900 nm. In another example, the one or more passbands can be discrete narrow passbands within a spectrum of wavelengths between about 500 nm to about 900 nm. Illumination system 412 can be further configured to provide one or more passbands having substantially constant center wavelength (CWL) values over a long period of time (e.g., over a lifetime of illumination system 412). Such configuration of illumination system 412 can help to prevent the shift of the actual CWL values from the desired CWL values, as discussed above, in current alignment systems. And, as a result, the use of constant CWL values can improve long-term stability and accuracy of alignment systems (e.g., inspection system 400) compared to the current alignment apparatuses.

**[0065]** In some aspects, beam splitter 414 can be configured to receive radiation beam 413 and split radiation beam 413 into at least two radiation sub-beams. For example, radiation beam 413 can be split into radiation sub-beams 415 and 417, as shown in FIG. 4A. Beam splitter 414 can be further configured to direct radiation sub-beam 415 onto a substrate 420 placed on a stage 422. In one example, the stage 422 is movable along direction 424. Radiation sub-beam 415 can be configured to illuminate an alignment mark or a target 418 located on substrate 420. Alignment mark or target 418 can be coated with a radiation sensitive film. In some aspects, alignment mark or target 418 can have one hundred and eighty degrees (i.e., 180°) symmetry. That is, when alignment mark or target 418 is rotated 180° about an axis of symmetry perpendicular to a plane of alignment mark or target 418, rotated alignment mark or target 418 can be substantially identical to an unrotated alignment mark or target 418. The target 418 on substrate 420 can be (a) a resist layer grating comprising bars that are formed of solid resist lines, or (b) a product layer grating, or (c) a composite grating stack in an overlay target structure comprising a resist grating overlaid or interleaved on a product layer grating. The bars can alternatively be etched into the substrate. This pattern is sensitive to chromatic aberrations in the lithographic projection apparatus, particularly the projection system PL, and illumination symmetry and the presence of such aberrations will manifest themselves in a variation in the printed grating. One in-line method used in device manufacturing for measurements of line width, pitch, and critical dimension makes use of a technique known as "scatterometry". Methods of scatterometry are described in Raymond et al., "Multiparameter Grating Metrology Using Optical Scatterometry", J. Vac. Sci. Tech. B, Vol. 15, no. 2, pp. 361-368 (1997) and Niu et al., "Specular Spectroscopic Scatterometry in DUV Lithography", SPIE, Vol. 3677 (1999), which are both incorporated by reference herein in their entireties. In scatterometry, light is reflected by periodic structures in the target, and the resulting reflection spectrum at a given angle is detected. The structure giving rise to the reflection spectrum is reconstructed, e.g. using Rigorous Coupled-Wave Analysis (RCWA) or by comparison to a library of patterns derived by simulation. Accordingly, the scatterometry data of the printed gratings is used to reconstruct the gratings. The parameters of the grating, such as line widths and shapes, can be input to the reconstruction process, performed by processing unit PU, from knowledge of the printing step and/or other scatterometry processes.

**[0066]** In some aspects, beam splitter 414 can be further configured to receive diffraction radiation beam 419 and split diffraction radiation beam 419 into at least two radiation sub-beams, according to an aspect. Diffraction radiation beam 419 can be split into diffraction radiation sub-beams 429 and 439, as shown in FIG. 4A.

**[0067]** It should be noted that even though beam splitter 414 is shown to direct radiation sub-beam 415 towards alignment mark or target 418 and to direct diffracted radiation sub-beam 429 towards interferometer 426, the disclosure is not so limiting. Other optical arrangements can be used to obtain the similar result of illuminating alignment mark or target 418 on substrate 420 and detecting an image of alignment mark or target 418.

**[0068]** In some aspects, illumination system 412 can comprise additional optical hardware that conditions the sourced radiation for subsequent irradiation of target 418. For example, illumination system 412 can comprise one or more lenses, polarizers, filters, or the like.

**[0069]** As illustrated in FIG. 4A, interferometer 426 can be configured to receive radiation sub-beam 417 and diffracted radiation sub-beam 429 through beam splitter 414. In an example aspect, diffracted radiation sub-beam 429 can be at least a portion of radiation sub-beam 415 that can be reflected from alignment mark or target 418. In an example of this aspect, interferometer 426 comprises any appropriate set of optical-elements, for example, a combination of prisms that can be configured to form two images of alignment mark or target 418 based on the received diffracted radiation sub-beam 429. It should be appreciated that a good quality image need not be formed. It can be enough to have the features of alignment mark 418 resolved. Interferometer 426 can be further configured to rotate one of the two images with respect to the other of the two images 180° and recombine the rotated and unrotated images interferometrically.

**[0070]** In some aspects, detector 428 can be configured to receive the recombined image via interferometer signal 427 and detect interference as a result of the recombined image when alignment axis 421 of inspection system 400 passes through a center of symmetry (not shown) of alignment mark or target 418. Such interference can be due to alignment mark or target 418 being 180° symmetrical, and the recombined image interfering constructively or destructively, according to an example aspect. Based on the detected interference, detector 428 can be further configured to determine a position of the center of symmetry of alignment mark or target 418 and consequently, detect a position of substrate

420. According to an example, alignment axis 421 can be aligned with an optical beam perpendicular to substrate 420 and passing through a center of image rotation interferometer 426. Detector 428 can be further configured to estimate the positions of alignment mark or target 418 by implementing sensor characteristics and interacting with wafer mark process variations.

**[0071]** In a further aspect, detector 428 determines the position of the center of symmetry of alignment mark or target 418 by performing one or more of the following measurements:

**[0072]** 1. measuring position variations for various wavelengths (position shift between colors);

**[0073]** 2. measuring position variations for various orders (position shift between diffraction orders); and

**[0074]** 3. measuring position variations for various polarizations (position shift between polarizations).

**[0075]** This data can be obtained using any type of alignment sensor, for example, a SMASH (SMart Alignment Sensor Hybrid) sensor, as described in U.S. Patent No. 6,961,116 that employs a self-referencing interferometer with a single detector and four different wavelengths, and extracts the alignment signal in software, or Athena (Advanced Technology using High order ENhancement of Alignment), as described in U.S. Patent No. 6,297,876, which directs each of seven diffraction orders to a dedicated detector, which are both incorporated by reference herein in their entireties.

**[0076]** In some aspects, beam analyzer 430 can be configured to receive and determine an optical state of diffracted radiation sub-beam 439. The optical state can be a measure of beam wavelength, polarization, or beam profile. Beam analyzer 430 can be further configured to determine a position of stage 422 and correlate the position of stage 422 with the position of the center of symmetry of alignment mark or target 418. As such, the position of alignment mark or target 418 and, consequently, the position of substrate 420 can be accurately known with reference to stage 422. Alternatively, beam analyzer 430 can be configured to determine a position of inspection system 400 or any other reference element such that the center of symmetry of alignment mark or target 418 can be known with reference to inspection system 400 or any other reference element. Beam analyzer 430 can be a point or an imaging polarimeter with some form of wavelength-band selectivity. In some aspects, beam analyzer 430 can be directly integrated into inspection system 400, or connected via fiber optics of several types: polarization preserving single mode, multimode, or imaging, according to other aspects.

**[0077]** In some aspects, beam analyzer 430 can be further configured to determine the overlay data between two patterns on substrate 420. One of these patterns can be a reference pattern on a reference layer. The other pattern can be an exposed pattern on an exposed layer. The reference layer can be an etched layer already present on substrate 420. The reference layer can be generated by a reference pattern exposed on the substrate by lithographic apparatus 100 and/or 100'. The exposed layer can be a resist layer exposed adjacent to the reference layer. The exposed layer can be generated by an exposure pattern exposed on substrate 420 by lithographic apparatus 100 or 100'. The exposed pattern on substrate 420 can correspond to a movement of substrate 420 by stage 422. In some aspects, the measured overlay data can also indicate an offset between the reference pattern and the exposure pattern. The measured overlay data can be used as calibration data to calibrate the exposure pattern exposed by lithographic apparatus 100 or 100', such that after the calibration, the offset between the exposed layer and the reference layer can be minimized.

**[0078]** In some aspects, beam analyzer 430 can be further configured to determine a model of the product stack profile of substrate 420, and can be configured to measure overlay, critical dimension, and focus of target 418 in a single measurement. The product stack profile contains information on the stacked product such as alignment mark, target 418, or substrate 420, and can include mark process variation-induced optical signature metrology that is a function of illumination variation. The product stack profile can also include product grating profile, mark stack profile, and mark asymmetry information. An example of beam analyzer 430 is Yieldstar$^{TM}$, manufactured by ASML, Veldhoven, The Netherlands, as described in U.S. Patent No. 8,706,442, which is incorporated by reference herein in its entirety. Beam analyzer 430 can be further configured to process information related to a particular property of an exposed pattern in that layer. For example, beam analyzer 430 can process an overlay parameter (an indication of the positioning accuracy of the layer with respect to a previous layer on the substrate or the positioning accuracy of the first layer with respective to marks on the substrate), a focus parameter, and/or a critical dimension parameter (e.g., line width and its variations) of the depicted image in the layer. Other parameters are image parameters relating to the quality of the depicted image of the exposed pattern.

**[0079]** In some aspects, an array of detectors (not shown) can be connected to beam analyzer 430, and allows the possibility of accurate stack profile detection as discussed below. For example, detector 428 can be an array of detectors. For the detector array, a number of options are possible: a bundle of multimode fibers, discrete pin detectors per channel, or CCD or CMOS (linear) arrays. The use of a bundle of multimode fibers enables any dissipating elements to be remotely located for stability reasons. Discrete PIN detectors offer a large dynamic range but each need separate pre-amps. The number of elements is therefore limited. CCD linear arrays offer many elements that can be read-out at high speed and are especially of interest if phase-stepping detection is used.

**[0080]** In some aspects, a second beam analyzer 430' can be configured to receive and determine an optical state of diffracted radiation sub-beam 429, as shown in FIG. 4B. The optical state can be a measure of beam wavelength, polarization, or beam profile. Second beam analyzer 430' can be identical to beam analyzer 430. Alternatively, second beam analyzer 430' can be configured to perform one or more of the functions of beam analyzer 430, such as determining a position of stage 422 and correlating the position of stage 422 with the position of the center of symmetry of alignment mark or target 418. As such, the position of alignment mark or target 418 and, consequently, the position of substrate 420, can be accurately known with reference to stage 422. Second beam analyzer 430' can also be configured to determine a position of inspection system 400, or any other reference element, such that the center of symmetry of alignment mark or target 418 can be known with reference to inspection system 400, or any other reference element.

**[0081]** In some aspects, second beam analyzer 430' can be directly integrated into inspection system 400, or it can be connected via fiber optics of several types: polarization preserving single mode, multimode, or imaging, according to other aspects. Alternatively, second beam analyzer 430' and beam analyzer 430 can be combined to form a single analyzer (not shown) configured to receive and determine the optical states of both diffracted radiation sub-beams 429 and 439.

**[0082]** In some aspects, processor 432 receives information from detector 428 and beam analyzer 430. Processor 432 can create a basic correction algorithm based on the information received from detector 428 and beam analyzer 430, including but not limited to the optical state of the illumination beam, the alignment signals, associated position estimates, and the optical state in the pupil, image, and additional planes. The pupil plane is the plane in which the radial position of radiation defines the angle of incidence and the angular position defines the azimuth angle of the radiation. Processor 432 can utilize the basic correction algorithm to characterize the inspection system 400 with reference to wafer marks and/or alignment marks 418.

**[0083]** A process as precise as nanofabrication typically entails multiple inspections of fabricated structures (e.g., target 418) on a wafer (e.g., substrate 420). The multiple inspections ensure sub-nanometer printing accuracy. It is also desirable to improve fabrication speeds without sacrificing sub-nanometer accuracy. Developing lithographic machines capable of higher throughput can offer a market edge to chip manufacturers and even alleviate global challenges, such as a global chip shortage.

**[0084]** In some aspects, the term "throughput" can be used herein to refer to a speed at which an amount of material or items pass through a system or process. The term "throughput" can characterize a speed of overall lithographic fabrication, a rate at which a wafer passes through a lithographic apparatus, a rate at which a wafer clears a particular fabrication step and moves on to the next step, or the like. Hence, "throughput" can be a performance marker of a lithographic apparatus.

**[0085]** It is desirable for lithographic systems to output as many products as possible in as little time as possible. Lithographic fabrication can comprise several complex processes. In some aspects, each process can comprise tradeoffs that balance desired qualities and drawbacks (e.g., sub-nanometer accuracy, high yield/throughput, slower fabrication, increased cost). To improve pattern-transfer accuracy, lithography can include inspection of printed marks on a substrate. Inspections performed by inspection system 400 can ascertain a conformity or accuracy of a printed pattern on a substrate or to align a substrate in order to properly receive a new pattern. However, the added time of the inspection operation can adversely impact throughput.

**[0086]** Consider aspects in which substrate 420 has multiple copies of target 418 to be measured by inspection system 400. Inspection system 400 is able to scan each target 418 one at a time. The aggregate inspection time can cripple throughput. Furthermore, the time spent moving target to target that can be responsible for most of the aggregate inspection time (e.g., 80% of the time is used on movement, 20% of the time is used on actual measurement).

**[0087]** In some aspects, inspection system 400 can be scaled up so as to have many of them side-by-side for the purposes of measuring more targets and reducing time spent on target-to-target movement. This can decrease the aggregate inspection time. However, some severe constraints can render the solution impractical. It is noted that inspection system 400 can comprise traditional free-space optical components (e.g., beam splitter 414, interferometer 426, lenses, polarizers, filters, or the like) to source, focus, collect, and direct radiation. More optical hardware is also often needed for correcting aberrations or otherwise adjusting radiation that has been scattered by target 418. Traditional free-space optical hardware is relatively large and bulky. A collection of such optical components arranged as in FIGS. 4A and 4B can result in a rather large optical system with a footprint that can exceed, for example, 35 mm x 35 mm. The space available for inspection systems within a lithographic scanner can be small—to the point that only one or a few inspection systems can be placed inside. To the extent that bulky free-space optical hardware can be manufactured smaller (which can present its own difficulties) for the purposes of reducing sensor-footprint, doing so can adversely impact the numerical aperture (NA) of inspection system 400. Inspection system 400 can rely on a large NA to collect pairs of diffraction orders (e.g., +1 and -1 diffraction orders). And pairs of diffraction orders can span a large range of diffraction angles.

**[0088]** For space saving, photonic integrated circuit (PIC) implementations have been proposed. Some examples of PIC sensors are described in WO 2021/259645 A1, filed on June 24, 2020, and WO 2022/258275A1, filed on May 9, 2022, which are both incorporated by reference herein in their entireties.

**[0089]** In some aspects, terms such as “integrated optics,” “integrated optical system,” “integrated optical circuit,” “photonic integrated circuit,” “integrated photonics,” “planar lightwave circuit,” “on-chip photonics,” or the like, can be used to refer to on-chip integrated devices that can propagate radiation signals without relying on traditional free space optical hardware. A PIC device can comprise, for example, waveguides disposed on a substrate (on-chip) such that radiation signals can propagate through the waveguide/substrate device. It should be understood that free space radiation can still interact with a PIC device (e.g., launching radiation, from free space, into the integrated optical device and vice versa). The waveguides can guide optical signals to other areas of the substrate, where the optical signals can be received and analyzed for measurement information. PIC devices can be made extremely small compared to bulky free space optics and at a fraction of the cost. Therefore, PIC sensors can be scaled in lithographic machines to increase the speed of scanning multiple marks.

**[0090]** In some aspects, as described above, PIC devices for illumination collection and detection can be designed so as to work around the NA issues (resulting from miniaturization of parts). However, designing PIC devices for illumination sourcing and guidance toward target 418 can present other issues that can hinder straightforward implementation of an all-inclusive PIC device that can be used for both sourcing and detecting illumination. Such challenges will be described below in reference to FIG. 5.

**[0091]** FIG. 5 shows an inspection system 500, according to some aspects. In some aspects, inspection system 500 can be an all-inclusive PIC-based sensor that is capable of guiding source radiation from a source toward a target 512 (e.g., a mark on a substrate 514). Inspection system 500 can comprise a photonic integrated circuit system 501. Photonic integrated circuit system 501 can comprise a board 502 (e.g., a chip, a substrate, a cladding, or the like), a waveguide system 504 with waveguides 504-n, a grating coupler (out) 506, a set of grating couplers (in) 508-m, and a detector 510. The indices n and m can have an integer value of 2 or greater. While only waveguides 504-1 and 504-2 along with grating couplers (in) 508-1 and 508-2 are shown (due to constraints of the cross-sectional-style drawing of FIG. 5), it is to be appreciated that additional waveguides and grating couplers can be implemented across a surface of board 502.

**[0092]** In some aspects, waveguide system 504, grating coupler (out) 506 and set of grating couplers (in) 508-m can be integrated on board 502, thereby forming the PIC portion of photonic integrated circuit system 501. Grating coupler (out) 506 and set of grating couplers (in) 508-m can be physically disposed at, and optically coupled to, their respective waveguides.

**[0093]** In some aspects, grating coupler (out) 506 can be coupled to one of the waveguides of waveguide system 504. The waveguide can be used to guide radiation from a radiation source (e.g., a laser) to grating coupler (out) 506. Grating coupler (out) 506 can allow a beam of radiation 516 to exit waveguide system 504 (e.g., outcoupling). Beam of radiation 516 can travel along an optical axis 518 (e.g., travel on-axis) that is perpendicular to a spread of target 512, a surface of substrate 514, and/or a surface of board 502. In some aspects, beam of radiation 516 can travel at a non-zero incidence angle (e.g., travel off-axis) (not shown) with respect to a spread of target 512, a surface of substrate 514, and/or a surface of board 502.

**[0094]** In some aspects, target 512 can scatter the incident radiation to produce scattered radiation 520-i (the index i can have an integer value of 2 or greater; e.g., shown are scattered radiation 520-1 and 520-2). Scattered radiation 520-1 and 520-2 can correspond to equal and opposite diffraction orders (e.g., -1 and +1, -2 and +2, or the like). Scattered radiation 520-1 and 520-2 can be received at corresponding ones of grating couplers (in) 508-1 and 508-2. Grating couplers (in) 508-1 and 508-2 can launch the scattered radiation into waveguide system 504 (incoupling). Waveguide system 504 can comprise combiners to combine and interfere the received radiation. Waveguide system 504 can send the received radiation to detector 510. In some aspects, detector 510 can be a detector system with multiple detectors. The detector 510 can generate a measurement signal based on the received radiation. Detector 510 is illustrated as being separated from board 502, but it is to be appreciated that detectors (e.g., photodiodes) can be implemented on board 502 (e.g., on-chip). Detector 510 can be disposed separate from the bulk of photonic integrated circuit 501 (e.g., remote location accessed via optical fibers).

**[0095]** In some aspects, a grating coupler is a specific example of a radiation coupler. Reference to grating couplers in aspects herein can be generalized as implementing suitable radiation couplers.

**[0096]** In some aspects, the measurement operations performed by inspection system 500 can be performed as described above in reference to inspection system 400 (FIGS. 4A and 4B) (e.g., collecting scattered diffraction orders from a target, combining and interfering diffraction orders, performing calculations to determine a property of a target based on the detected radiation, or the like). The difference between inspection systems 400 and 500 is in the optical hardware (e.g., traditional free-space optics versus PIC-based hardware).

**[0097]** Referring to the on-axis aspect as an example, the source radiation that feeds beam of radiation 516 can comprise multiple wavelengths (e.g., two or more). In some aspects, it is desirable to use several wavelengths (e.g., ten or more) and two polarizations on-axis to obtain highly detailed information about target 512. It is desirable to irradiate target 512 using a beam of radiation with multiple wavelengths, as each wavelength provides different information about target 512. It is desirable to have each wavelength be incident on target 512 in a consistent manner (e.g., each wavelength has the same angle of incidence, or distribution of angles of incidence, on target 512). However, it can be challenging to design grating coupler (out) 506 so as to be able to handle a multitude of wavelengths in an efficient and consistent manner. A grating coupler designed for one wavelength can reject, or otherwise misdirect, radiation with a different wavelength. That is, a grating coupler design that works for one wavelength can be unsuitable for another wavelength when used in inspection system 500.

**[0098]** Therefore, some aspects described herein implement a hybrid approach, realizing the desirable features of both traditional free-space optics and PIC-based hardware while mitigating the drawbacks of each.

**[0099]** *Example Optical-Photonic Hybrid Inspection System*

**[0100]** FIG. 6 shows an inspection system 600, according to some aspects. In some aspects, inspection system 600 can borrow features of inspection systems 400 and 500 (FIGS. 4A, 4B, and 5) so that free-space optical hardware from inspection system 400 for sourcing radiation is combined with PIC-based hardware from inspection system 500 for detection. Therefore, inspection system 600 can incorporate some features described in reference to FIGS. 4A, 4B, and 5.

**[0101]** In some aspects, inspection system 600 can comprise a photonic integrated circuit system 601 and a radiation system 622. Photonic integrated circuit system 601 can comprise a board 602, a waveguide system 604 with waveguides 604-n (e.g., waveguides 604-1 and 604-2 or first and second waveguides), a set of grating couplers (in) 608-m (e.g., grating couplers (in) 608-1 and 608-2 or first and second grating couplers (in)), and a detector 610. Features of the PIC portion of photonic integrated circuit system 601 can be inferred from the description of photonic integrated circuit system 501 (FIG. 5).

**[0102]** In some aspects, radiation can comprise a radiation source 624 (e.g., a multi-wavelength laser) and an optical system 626. Optical system 626 is envisaged as the free-space optics portion of inspection system 600. As explained above, the radiation-sourcing portion of a sensor does not suffer the same NA constraints as the radiation-collection portion. Since optical system 626 is part of the radiation-sourcing portion, it is possible to reduce the footprint of optical system 626, with the ensuing NA reduction being an acceptable tradeoff. Advances in optical manufacturing techniques can now produce miniaturized lenses and other free-space optics with small footprints. Optical system 626 can comprise a lens 628 and a lens 630 (e.g., first and second lenses).

**[0103]** In some aspects, at least a portion of inspection system 600 can be implemented as sensor IF1, IF2, or IFD in lithographic apparatus 100 and 100' (FIGS. 1A, 1B, and 2) to monitor a wafer undergoing lithographic pattern transfer (e.g., measuring a position of a wafer or a mark thereon). For example, any of sensors IF1, IF2, and IFD (FIGS. 1A and 1B) can comprise optical system 626. To facilitate shipment, installation, and maintenance, optical system 626 can be modular. Then, optical system 626 can be serviced without having to disturb the other portions of inspection system 600. Radiation source 624 can be disposed remote from optical system 626 and/or lithographic apparatus 100 and 100' (FIGS. 1A, 1B, and 2). To feed optical system 626 with radiation, radiation system 622 can comprise an optical fiber 632 (e.g., a multimode fiber) to guide the sourced radiation from radiation source 624 to optical system 626.

**[0104]** In some aspects, optical system 626 can comprise an adjustable fiber connector 634, an adjustable lens support 636 (e.g., first adjustable lens support), and/or an adjustable lens support 638 (e.g., second adjustable lens support). Adjustable fiber connector 632 can be a suitable connector that allows repeatable and consistent alignment upon connection with optical fiber 632 (e.g., a pigtail connector). Adjustable fiber connector 632 and adjustable lens supports 636 and 638 can comprise suitable systems of actuation members (e.g., screws, inline actuator, rotation actuators, and the like) to align a beam of radiation 616.

**[0105]** In some aspects, radiation source 624 can generate beam of radiation 616. Beam of radiation 616 can travel approximately along an optical axis 618 (dashed line) that is perpendicular to a spread of target 612, a surface of substrate 614, and/or a surface of board 602. In some aspects, beam of radiation 616 can travel at a non-zero incidence angle (e.g., travel off-axis) (not shown) with respect to a spread of target 612, a surface of substrate 614, and/or a surface of board 602. In any case, adjustable fiber connector 632 and adjustable lens supports 636 and 638 can allow adjustments to the alignment of beam of radiation 616 to achieve a desired angle of incidence on target 612. Target 612 can scatter the incident radiation to produce scattered radiation 620-i (e.g., scattered radiation 620-1 and 620-2).

**[0106]** In some aspects, board 602 can comprise an aperture 640. Aperture 640 access so that beam of radiation 616 can travel from optical system 626 to target 612 unobstructed. Aperture 640 can be any suitable structure that allows transmission of beam of radiation 616 (e.g., a material that is transparent at the relevant wavelengths, a void (hole), or the like). For clarity, some envisaged elements related to the conditioning of beam of radiation 616 are not shown (e.g., filters, polarizers, or the like).

**[0107]** In some aspects, target 612 scatter radiation along non-specular directions (e.g., at diffraction angles). Target 612 can accomplish this by comprising one or more diffraction patterns (e.g., gratings, arrays of gratings, two-dimensional gratings, periodic structures, or the like). Shown are scattered radiation 620-i (shown are scattered radiation 620-1 and 620-2; additional scattering directions are also envisaged). Scattered radiation 620-1 can be received at grating coupler (in) 608-1. Grating coupler (in) 608-1 can launch the received scattered radiation 620-1 into waveguide 604-1. Scattered radiation 620-2 can be received at grating coupler (in) 608-2. Grating coupler (in) 608-2 can launch the received scattered radiation 620-2 into waveguide 604-2. Waveguides 604-1 and 604-2 can guide the scattered radiation to a combiner so as to interfere the radiation. Combiners of waveguide system 604 will be described in more detail below in reference to FIG. 8. The combined radiation can then be guided by waveguide system 604 to detector 610. Detector 610 can receive the scattered radiation from waveguide system 604 and generate one or more measurement signals. The measurement signals (e.g., a voltage signal, current signal, AC signal, or the like) can be processed and analyzed in post-processing (e.g., using processor 432 (FIG. 4)). A property of target 612 (e.g., alignment position) can be determined based on the analysis of the measurement signal.

**[0108]** In some aspects, as a spot of beam or radiation 616 is moved/scanned across target 612, the interference of the combined scattered radiation 620-1 and 620-2 within waveguide system 604 can evolve over the duration of the scan (the above-mentioned SMASH sensor is an example of such a self-referencing interferometric sensor). As a result of the scanning motion, the measurement signal(s) from detector 610 can have AC modulation characteristics. That is, the measurement signal(s) generated by detector 610 can be AC signals. A property of target 612 (e.g., an alignment position) can be extracted from the characteristics of the AC signal (e.g., from the phase of the AC signal).

**[0109]** FIGS. 7A and 7B show a portion of an inspection system 700, according to some aspects. In some aspects, the views in FIGS. 7A and 7B can represent more detailed expanded views of a portion of inspection system 600 (FIG. 6) (some omissions may have been made for clarity of drawing). Structures and functions of some elements of FIGS. 7A and 7B can be inferred from the above description of FIG. 6. Such elements can include a photonic integrated circuit system 701, a board 702, a detector 710, a target 712, a substrate 714, a beam of radiation 716, an optical axis 718, scattered radiation 720-i (e.g., 720-1 and 720-2), an optical system 726, a lens 728, a lens 730, an optical fiber 732, an adjustable fiber connector 734, an adjustable lens support 736, and an adjustable lens support 738. For ease of reference, matching elements between FIGS. 6 and 7A/7B can have reference numbers that share the two right-most numeric digits.

**[0110]** In some aspects, optical fiber 732 can comprise a ferrule 742. Ferrule 742 is an optical fiber structure that can allow stable insertion and connection at adjustable fiber connector 734. A precise alignment of beam of radiation 716 along optical axis 718 is desirable. To achieve the alignment, multiple adjustment members 736 can be used for translation and/or rotation of the various optical components in optical system 726. A securing system with fasteners 748 can be used to maintain alignment positions once set, thereby preventing a drift of the positions once aligned. Adjustment members 746 and fasteners 748 can be adjusted manually and/or mechanized via high-precision actuators. While FIG. 7 shows fourteen adjustment members 746 and corresponding fasteners 748, implementations with more or fewer adjustment members and fasteners are envisaged.

**[0111]** In some aspects, adjustable fiber connector 734 can adjust a rotation and/or translation position of optical fiber 732 as to align beam of radiation 716 along optical axis 718. Rotations can include, for example, rotations about the X, Y, and/or Z axes (Rx, Ry, and Rz). Translations can include, for example, translations along the Z axis, which can affect the focus of beam of radiation 716 (e.g., a distance between an end of optical fiber 732 and lens 728). Position adjustments of optical fiber 732 can be achieved using one or more adjustment members 746 of adjustable fiber connector 734. Affixing or securing a position of optical fiber 732 can be achieved using one or more fasteners 748 of adjustable fiber connector 734.

**[0112]** In some aspects, adjustable lens support 736 can adjust a rotation and/or translation position of lens 728 to achieve desired optical characteristics for beam of radiation 716. Translations can include, for example, translations along the X, Y, and Z axes, which can affect the focus of beam of radiation 716. Position adjustments of lens 728 can be achieved using one or more adjustment members 746 of adjustable lens support 736. Affixing or securing a position of lens 728 can be achieved using one or more fasteners 748 of adjustable lens support 736. In some aspects, lens 730 can be adjusted in a similar manner using adjustable lens support 738 and corresponding one or more adjustment members 746 and one or more fasteners 748.

**[0113]** In some aspects, the surface of the PIC portion (e.g., board 702) can also be adjusted. A concern is that beam of radiation 716 can clip board 702 when passing through aperture 740 when board 702 is misaligned. Also, as was shown in FIG. 6, scattered radiation is to be received at grating couplers and, therefore, performance can suffer if board 702 is misaligned. Board 702 can be adjusted (rotation and/or translation) using corresponding one or more adjustment members 746 and one or more fasteners 748. Rotations can include, for example, rotations about the X, Y, and/or Z axes (Rx, Ry, and Rz). Translations can include, for example, translations along the X, Y, and/or Z axes.

**[0114]** In some aspects, translations and rotations about axes can be referred to as "degrees of freedom." Translational degrees of freedom can include first, second, and third degrees of freedom (e.g., a degree of freedom for each of X, Y, and Z). Rotational degrees of freedom can include fourth, fifth, and sixth degrees of freedom (e.g., a degree of freedom for each of Rx, Ry, and Rz).

**[0115]** In some aspects, one or more fasteners 748 can be used to fasten one or more adjustment members 746 (e.g., to prevent adjustment members from moving). In some aspects, one or more fasteners 748 can be used to press against any of the adjustable structure(s) disclosed herein so as to prevent said adjustable structure from moving. In some aspects, inspection system 700 can also comprise one or more adjustment members 747 (shown in FIG. 7B). Adjustment members 747 can combine the adjustability of adjustment members 746 and the fastening function of fasteners 748.

**[0116]** While it is envisaged that inspection system 700 can be implemented according to any suitable design, FIG. 7B provides an example design in perspective view. It is to be appreciated that some elements can be out of view (e.g., some adjustment members or fasteners) due to the perspective of

FIG. 7B. An additional element that appears in FIG. 7B is an optical system 750 (e.g., a second optical system). Optical system 750 can comprise a suitable radiation guide (e.g., waveguide(s), optical fiber(s), or the like), to direct the collected scattered radiation 720-i to detector 710. Detector 710 is shown to be implemented as an element that is separate from the PIC portion. However, some embodiments can have detectors implemented on-chip (on board 702).

**[0117]** In some aspects, adjustment members 747 can be implemented as opposing pairs. As one of the pairs of adjustment members 747 is loosened, a given adjustable structure is adjusted in a desired direction. Then the opposing one of the pairs of adjustment members 747 can be tightened in order to secure a position of the adjustable structure.

**[0118]** FIG. 8 shows a photonic integrated circuit system 801, according to some aspects. In some aspects, photonic integrated circuit system 801 can represent a layout view of photonic integrated circuit systems 601 and 701 (FIGS. 6 and 7). Photonic integrated circuit system 801 can comprise a board 802, a waveguide system 804 comprising waveguides 804-n, a set of grating couplers (in) 808 comprising grating couplers (in) 808-m, an aperture 840, and a connector 852.

**[0119]** In some aspects, target 612/712 (FIGS. 6, 7A, and 7B) can comprise multiple diffraction patterns that can scatter radiation along more than one plane (e.g., XZ plane and YZ plane) (e.g., can be achieved via an array of gratings having orientations in different directions). Due to limitations of perspective, the examples in FIGS. 6, 7A, and 7B are only able to show scattered radiation 620/720 being scattered along the YZ plane.

**[0120]** In some aspects, in order to capture scattered radiation along multiple directions caused by a target structure (e.g., caused by grating pitch and/or orientation), wavelength (affects diffraction angle), higher orders (e.g., 2nd order is a different angle from 1st order), or the like, photonic integrated circuit system 801 can comprise a corresponding number of waveguides and grating couplers (in). For the incoupling operation, FIG. 8 shows a setup that comprises waveguides 804-1 to 804-8 and grating couplers (in) 808-1 to 808-8. In some aspects, grating couplers (in) 808-1 and 808-2 can be used to receive scattered radiation corresponding to +1 and -1 orders along the YZ plane and launch the scattered radiation into waveguides 804-1 and 804-2, respectively. Grating couplers (in) 808-3 and 808-4 can be used to receive scattered radiation corresponding to +1 and -1 orders along the XZ plane and launch the scattered radiation into waveguides 804-3 and 804-4, respectively. Grating couplers (in) 808-5 and 808-6 can be used to receive scattered radiation corresponding to +2 and -2 orders along the YZ plane and launch the scattered radiation into waveguides 804-5 and 804-6, respectively. Grating couplers (in) 808-7 and 808-8 can be used to receive scattered radiation corresponding to +2 and -2 orders along the XZ plane and launch the scattered radiation into waveguides 804-7 and 804-8, respectively.

**[0121]** In some aspects, photonic integrated circuit system 801 can comprise combiners 852-j (e.g., combiners 852-1 to 852-4). Combiner 852-1 can combine the scattered radiation from waveguides 804-1 and 804-2 (e.g., combine a portion of the scattered radiation with another portion of the scattered radiation). Combiner 852-2 can combine the scattered radiation from waveguides 804-3 and 804-4. Combiner 852-3 can combine the scattered radiation from waveguides 804-5 and 804-6. Combiner 852-4 can combine the scattered radiation from waveguides 804-7 and 804-8.

**[0122]** In some aspects, photonic integrated circuit system 801 can also comprise a connector 854. Waveguide system 804 can also comprise waveguides 804-9, 804-10, 804-11, and 804-12. Waveguide 804-9 can receive the combined scattered radiation from combiner 852-1 and guide it to connector 854. Waveguide 804-10 can receive the combined scattered radiation from combiner 852-2 and guide it to connector 854. Waveguide 804-11 can receive the combined scattered radiation from combiner 852-3 and guide it to connector 854. Waveguide 804-12 can receive the combined scattered radiation from combiner 852-4 and guide it to connector 854. Optical system 750 (FIG. 7B) can connect to connector 854. Connector 854 can send the combined radiation to respective detectors at detector 710 (FIG. 7B) via optical system 750. In some aspects, detectors can be fabricated on board 802. It is desirable to choose implementations that reduce the volume and footprint area of metrology systems 600/700 (FIGS. 6, 7A, and 7B). The footprint area can be defined as an area that is parallel to the surface of substrate 714 (FIG. 7A).

**[0123]** In some aspects, by implementing a hybrid inspection system that uses both traditional optics and photonic integrated circuits, the footprint of the inspection system can be reduced to, for example, approximately 20 mm x 20 mm or less.

**[0124]** The embodiments may further be described using the following clauses:

1. A lithographic apparatus comprising:

a projection system configured to project an image of a patterning device onto a substrate; and

an inspection system comprising:

a radiation system configured to direct radiation toward a target on the substrate to generate scattered radiation from the target, the radiation system comprising:

a radiation source configured to generate the radiation; and

an optical system configured to focus the radiation on the target; and

a photonic integrated circuit system configured to receive the scattered radiation from the target, the photonic integrated circuit system comprising:

a waveguide system integrated on a board;

a radiation coupler disposed at a waveguide of the waveguide system and configured to launch at least a portion of the scattered radiation into the waveguide system; and

a detector system configured to receive the scattered radiation from the waveguide system and to generate a measurement signal based on the scattered radiation.

2. The lithographic apparatus of clause 1, wherein:

the radiation source is further configured generate the radiation at multiple wavelengths;

the optical system is further configured to focus the radiation having the multiple wavelengths;

the radiation coupler is structured to transmit a first one of the multiple wavelengths;

the photonic integrated circuit system further comprises another radiation coupler disposed on another waveguide of the waveguide system, structured to transmit a second one of the wavelengths, and configured to launch another portion of the scattered radiation into the waveguide system.

3. The lithographic apparatus of clause 1, wherein the photonic integrated circuit system further comprises:

another radiation coupler disposed on another waveguide of the waveguide system and configured to launch another portion of the scattered radiation into the waveguide system; and

a combiner configured to combine the portion of the scattered radiation and the another portion of the scattered radiation.

4. The lithographic apparatus of clause 1, wherein:

the radiation source comprises an optical fiber configured to guide the radiation to the optical system; and

the optical system comprises free space optics comprising an adjustable fiber connector configured to couple the optical fiber to the free space optics and to adjust a position of the optical fiber to align the radiation to an optical axis of the free space optics.

5. The lithographic apparatus of clause 4, wherein the adjustable fiber connector comprises an adjustment member configured to adjust a distance between an end of the optical fiber and a lens of the optical system.

6. The lithographic apparatus of clause 1, wherein the optical system comprises:

a first lens;

a first adjustable lens support configured to support the first lens and to adjust an optical alignment of the first lens;

a second lens; and

a second adjustable lens support configured to support the second lens and to adjust an optical alignment of the second lens.

7. The lithographic apparatus of clause 1, wherein the photonic integrated circuit system comprises an aperture configured to transmit the radiation.

8. The lithographic apparatus of clause 1, wherein:

the inspection system further comprises an optical fiber system;

the detector system is located remote relative to the board; and

the optical fiber system is configured to guide the scattered radiation from the waveguide system to the detector system.

9. The lithographic apparatus of clause 1, wherein the detector system is integrated on the board.

10. An inspection system comprising:

a radiation system configured to direct radiation toward a target to generate scattered radiation from the target, the radiation system comprising;

a radiation source configured to generate the radiation; and

an optical system configured to focus the radiation on the target; and

a photonic integrated circuit system configured to receive the scattered radiation from the target, the photonic integrated circuit system comprising:

a waveguide system integrated on a board;

a radiation coupler disposed at a waveguide of the waveguide system and configured to launch at least a portion of the scattered radiation into the waveguide system; and

a detector system configured to receive the scattered radiation from the waveguide system and to generate a measurement signal based on the scattered radiation.

11. The inspection system of clause 10, wherein:

the radiation source is further configured generate the radiation at multiple wavelengths;

the optical system is further configured to focus the radiation having the multiple wavelengths;

the radiation coupler is structured to transmit a first one of the multiple wavelengths;

the photonic integrated circuit system further comprises another radiation coupler disposed on another waveguide of the waveguide system, structured to transmit a second one of the wavelengths, and configured to launch another portion of the scattered radiation into the waveguide system.

12. The inspection system of clause 10, wherein the photonic integrated circuit system further comprises:

another radiation coupler disposed on another waveguide of the waveguide system and configured to launch another portion of the scattered radiation into the waveguide system; and

a combiner configured to combine the portion of the scattered radiation and the another portion of the scattered radiation.

13. The inspection system of clause 10, wherein:

the radiation source comprises an optical fiber configured to guide the radiation to the optical system; and

the optical system comprises free space optics comprising an adjustable fiber connector configured to couple the optical fiber to the free space optics and to adjust a position of the optical fiber to align the radiation to an optical axis of the free space optics.

14. The inspection system of clause 13, wherein the adjustable fiber connector comprises an adjustment member configured to adjust a distance between an end of the optical fiber and a lens of the optical system.

15. The inspection system of clause 10, wherein the optical system comprises:

a first lens;

a first adjustable lens support configured to support the first lens and to adjust an optical alignment of the first lens;

a second lens; and

a second adjustable lens support configured to support the second lens and to adjust an optical alignment of the second lens.

16. The inspection system of clause 10, wherein the photonic integrated circuit system comprises an aperture configured to transmit the radiation.

17. The inspection system of clause 10, further comprising an optical fiber system, wherein the detector system is located remote relative to the board and wherein the optical fiber system is configured to guide the scattered radiation from the waveguide system to the detector system.

18. An inspection system comprising:

an optical system configured to focus radiation on a target to generate scattered radiation, the optical system comprising:

a first adjustable lens support configured to adjust an optical alignment of a first lens;

a second adjustable lens support configured to adjust an optical alignment of a second lens; and

an adjustable fiber connector configured to direct a beam of radiation from an optical fiber to the optical system and to adjust a position of the optical fiber to align the beam along an optical axis of the optical system;

a photonic integrated circuit system configured to receive the scattered radiation from the target, the photonic integrated circuit system comprising:

a waveguide system integrated on a board and configured to guide the scattered radiation to a detector system; and

a radiation coupler disposed at a waveguide of the waveguide system and configured to launch the scattered radiation into the waveguide system.

19. The inspection system of clause 18, wherein the adjustable fiber connector comprises an adjustment member configured to adjust the position of the optical fiber with respect to a translational degree of freedom.

20. The inspection system of clause 18, wherein the adjustable fiber connector comprises an adjustment member configured to adjust the position of the optical fiber with respect to a rotational degree of freedom.

21. The inspection system of clause 18, wherein the adjustable fiber connector comprises a securing system configured to maintain a position of the optical fiber once set thereby preventing a drift of the position of the optical fiber once aligned.

22. The inspection system of clause 18, further comprising an optical fiber system, wherein the detector system is located remote relative to the board and wherein the optical fiber system is configured to guide the scattered radiation from the waveguide system to the detector system.

**[0125]** The terms “radiation,” “beam,” “light,” “illumination,” or the like can be used herein to refer to one or more types of electromagnetic radiation, for example, ultraviolet (UV) radiation (for example, having a wavelength $\lambda$ of 365, 248, 193, 157 or 126 nm), extreme ultraviolet (EUV or soft X-ray) radiation (for example, having a wavelength in the range of 5-100 nm such as, for example, 13.5 nm), or hard X-ray working at less than 5 nm, as well as particle beams, such as ion beams or electron beams. The visible range, IR, mid-IR, or the like, can be used for inspection (e.g., alignment sensors). Generally, radiation having wavelengths between about 400 to about 700 nm is considered visible radiation; radiation having wavelengths between about 780-3000 nm (or larger) is considered IR radiation. UV refers to radiation with wavelengths of approximately 100-400 nm. Within lithography, the term "UV" also applies to the wavelengths that can be produced by a mercury discharge lamp: G-line 436 nm; H-line 405 nm; and/or, I-line 365 nm. Vacuum UV, or VUV (i.e., UV absorbed by gas), refers to radiation having a wavelength of approximately 100-200 nm. Deep UV (DUV) generally refers to radiation having wavelengths ranging from 126 nm to 428 nm, and in some aspects, an excimer laser can generate DUV radiation used within a lithographic apparatus. It should be appreciated that radiation having a wavelength in the range of, for example, 5-20 nm relates to radiation with a certain wavelength band, of which at least part is in the range of 5-20 nm.

**[0126]** Although some aspects of the present disclosure are described in the context of lithographic apparatuses in the manufacture of ICs, it should be understood that lithographic apparatuses described herein can be used in other applications, for example, in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, flat-panel displays, LCDs, thin-film magnetic heads, quantum computing, ion/atom trapping, light detection and ranging, etc. Those skilled in the art will appreciate that, in the context of such alternative applications, any use of the terms "wafer" or "die" herein can be considered as specific examples of the more general terms "substrate" or "target portion", respectively. A substrate can be processed before or after exposure in, for example, a track unit (a tool that typically applies a layer of resist to a substrate and develops the exposed resist) and/or a metrology unit. Where applicable, aspects disclosed herein can be applied to such and other substrate processing tools. Furthermore, a substrate can be processed more than once, for example in order to create a multi-layer IC, so that the term substrate used herein can also refer to a substrate that already contains multiple processed layers.

**[0127]** Furthermore, although some aspects of the present disclosure are described in the context of optical lithography, it should be understood that aspects of the present disclosure are not limited to optical lithography. For example, in imprint lithography, a topography in a patterning device defines the pattern created on a substrate. The topography of the patterning device can be pressed into a layer of resist supplied to the substrate whereupon the resist is cured by applying electromagnetic radiation, heat, pressure or a combination thereof. The patterning device is moved out of the resist leaving a pattern in it after the resist is cured.

**[0128]** It is to be understood that the phraseology or terminology herein is for the purpose of description and not of limitation, such that the terminology or phraseology of the present specification is to be interpreted by those skilled in relevant art(s) in light of the teachings herein.

**[0129]** The present disclosure has been described above with the aid of functional building blocks illustrating the implementation of specified functions and relationships thereof. The boundaries of these functional building blocks have been arbitrarily defined herein for the convenience of the description. Alternate boundaries can be defined so long as the specified functions and relationships thereof are appropriately performed. The foregoing description of specific aspects will so fully reveal the general nature of the present disclosure that others can, by applying knowledge within the skill of the art, readily modify and/or adapt for various applications such specific aspects, without undue experimentation and without departing from the general concept of the present disclosure. Therefore, such adaptations and modifications are intended to be within the meaning and range of equivalents of the disclosed aspects, based on the teaching and guidance presented herein.

**[0130]** It is to be understood that the Detailed Description section, and not the Summary and Abstract sections, is intended to be used to interpret the claims. The Summary and Abstract sections can set forth one or more, but not necessarily all, aspects of the present disclosure as contemplated by the inventor(s), and thus, are not intended to limit the present disclosure and the appended claims in any way. The breadth and scope of the protected subject matter should not be limited by any of the above-described aspects, but should be defined in accordance with the following claims and their equivalents.

CLAIMS

1. A lithographic apparatus comprising:

a projection system configured to project an image of a patterning device onto a substrate; and

an inspection system comprising:

a radiation system configured to direct radiation toward a target on the substrate to generate scattered radiation from the target, the radiation system comprising:

a radiation source configured to generate the radiation; and

an optical system configured to focus the radiation on the target; and

a photonic integrated circuit system configured to receive the scattered radiation from the target, the photonic integrated circuit system comprising:

a waveguide system integrated on a board;

a radiation coupler disposed at a waveguide of the waveguide system and configured to launch at least a portion of the scattered radiation into the waveguide system; and

a detector system configured to receive the scattered radiation from the waveguide system and to generate a measurement signal based on the scattered radiation.

2. The lithographic apparatus of claim 1, wherein:

the radiation source is further configured generate the radiation at multiple wavelengths;

the optical system is further configured to focus the radiation having the multiple wavelengths;

the radiation coupler is structured to transmit a first one of the multiple wavelengths;

the photonic integrated circuit system further comprises another radiation coupler disposed on another waveguide of the waveguide system, structured to transmit a second one of the wavelengths, and configured to launch another portion of the scattered radiation into the waveguide system.

3. The lithographic apparatus of claim 1, wherein the photonic integrated circuit system further comprises:

another radiation coupler disposed on another waveguide of the waveguide system and configured to launch another portion of the scattered radiation into the waveguide system; and

a combiner configured to combine the portion of the scattered radiation and the another portion of the scattered radiation.

4. The lithographic apparatus of claim 1, wherein:

the radiation source comprises an optical fiber configured to guide the radiation to the optical system; and

the optical system comprises free space optics comprising an adjustable fiber connector configured to couple the optical fiber to the free space optics and to adjust a position of the optical fiber to align the radiation to an optical axis of the free space optics.

5. The lithographic apparatus of claim 4, wherein the adjustable fiber connector comprises an adjustment member configured to adjust a distance between an end of the optical fiber and a lens of the optical system.

6. The lithographic apparatus of claim 1, wherein the optical system comprises:

a first lens;

a first adjustable lens support configured to support the first lens and to adjust an optical alignment of the first lens;

a second lens; and

a second adjustable lens support configured to support the second lens and to adjust an optical alignment of the second lens.

7. The lithographic apparatus of claim 1, wherein the photonic integrated circuit system comprises an aperture configured to transmit the radiation.

8. The lithographic apparatus of claim 1, wherein:

the inspection system further comprises an optical fiber system;

the detector system is located remote relative to the board; and

the optical fiber system is configured to guide the scattered radiation from the waveguide system to the detector system.

9. The lithographic apparatus of claim 1, wherein the detector system is integrated on the board.

10. An inspection system comprising:

a radiation system configured to direct radiation toward a target to generate scattered radiation from the target, the radiation system comprising;

a radiation source configured to generate the radiation; and

an optical system configured to focus the radiation on the target; and

a photonic integrated circuit system configured to receive the scattered radiation from the target, the photonic integrated circuit system comprising:

a waveguide system integrated on a board;

a radiation coupler disposed at a waveguide of the waveguide system and configured to launch at least a portion of the scattered radiation into the waveguide system; and

a detector system configured to receive the scattered radiation from the waveguide system and to generate a measurement signal based on the scattered radiation.

11. The inspection system of claim 10, wherein:

the radiation source is further configured generate the radiation at multiple wavelengths; the optical system is further configured to focus the radiation having the multiple wavelengths;

the radiation coupler is structured to transmit a first one of the multiple wavelengths;

the photonic integrated circuit system further comprises another radiation coupler disposed on another waveguide of the waveguide system, structured to transmit a second one of the wavelengths, and configured to launch another portion of the scattered radiation into the waveguide system.

12. The inspection system of claim 10, wherein the photonic integrated circuit system further comprises:

another radiation coupler disposed on another waveguide of the waveguide system and configured to launch another portion of the scattered radiation into the waveguide system; and

a combiner configured to combine the portion of the scattered radiation and the another portion of the scattered radiation.

13. The inspection system of claim 10, wherein:

the radiation source comprises an optical fiber configured to guide the radiation to the optical system; and

the optical system comprises free space optics comprising an adjustable fiber connector configured to couple the optical fiber to the free space optics and to adjust a position of the optical fiber to align the radiation to an optical axis of the free space optics.

14. The inspection system of claim 13, wherein the adjustable fiber connector comprises an adjustment member configured to adjust a distance between an end of the optical fiber and a lens of the optical system.

15. The inspection system of claim 10, wherein the optical system comprises:

a first lens;

a first adjustable lens support configured to support the first lens and to adjust an optical alignment of the first lens;

a second lens; and

a second adjustable lens support configured to support the second lens and to adjust an optical alignment of the second lens.

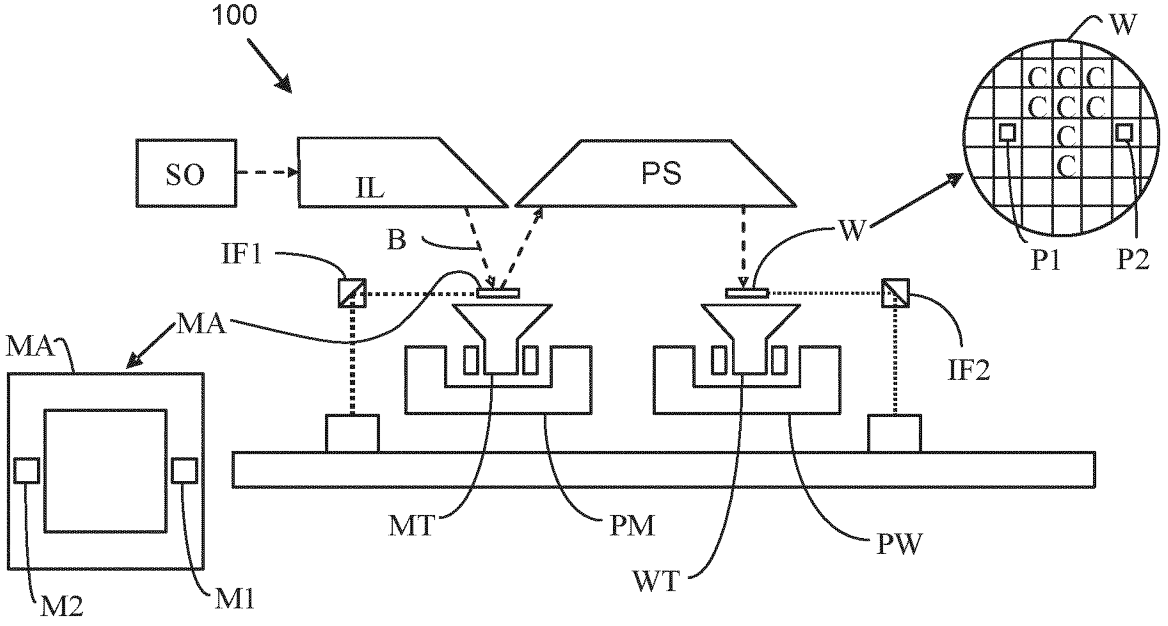

FIG. 1A

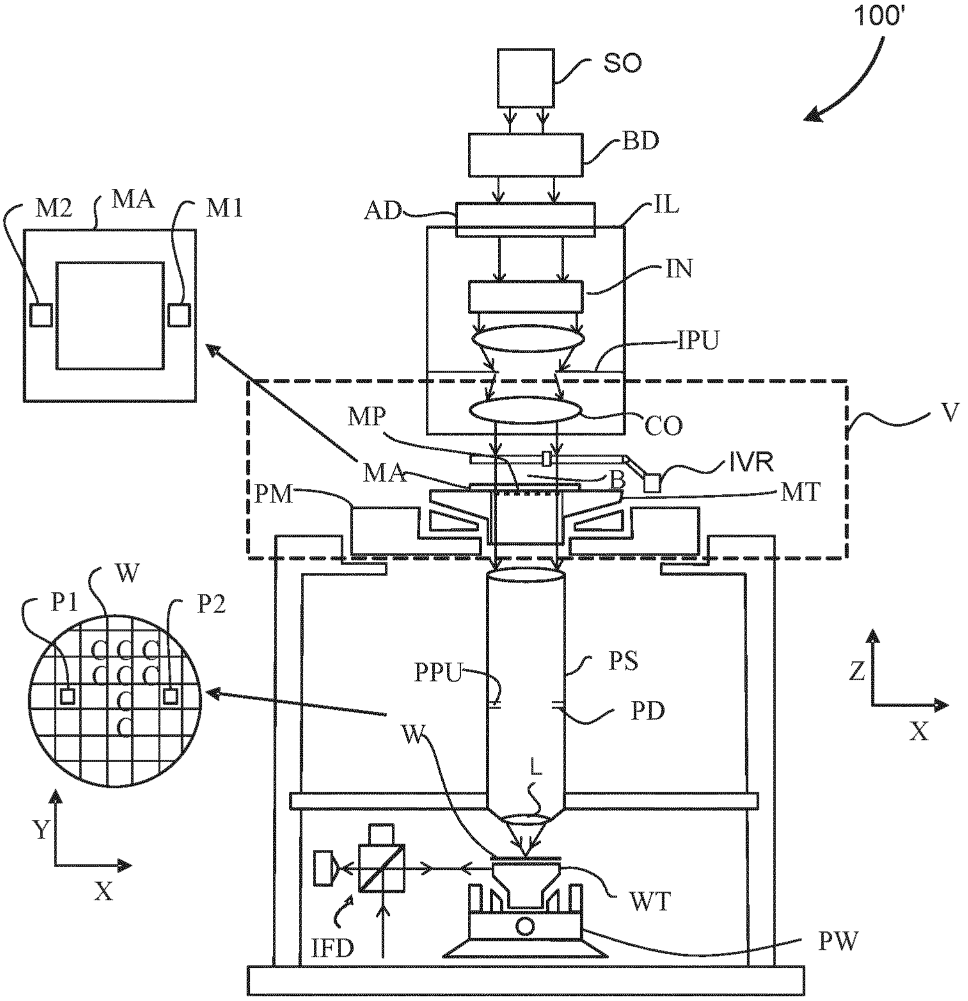
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FIG. 1B

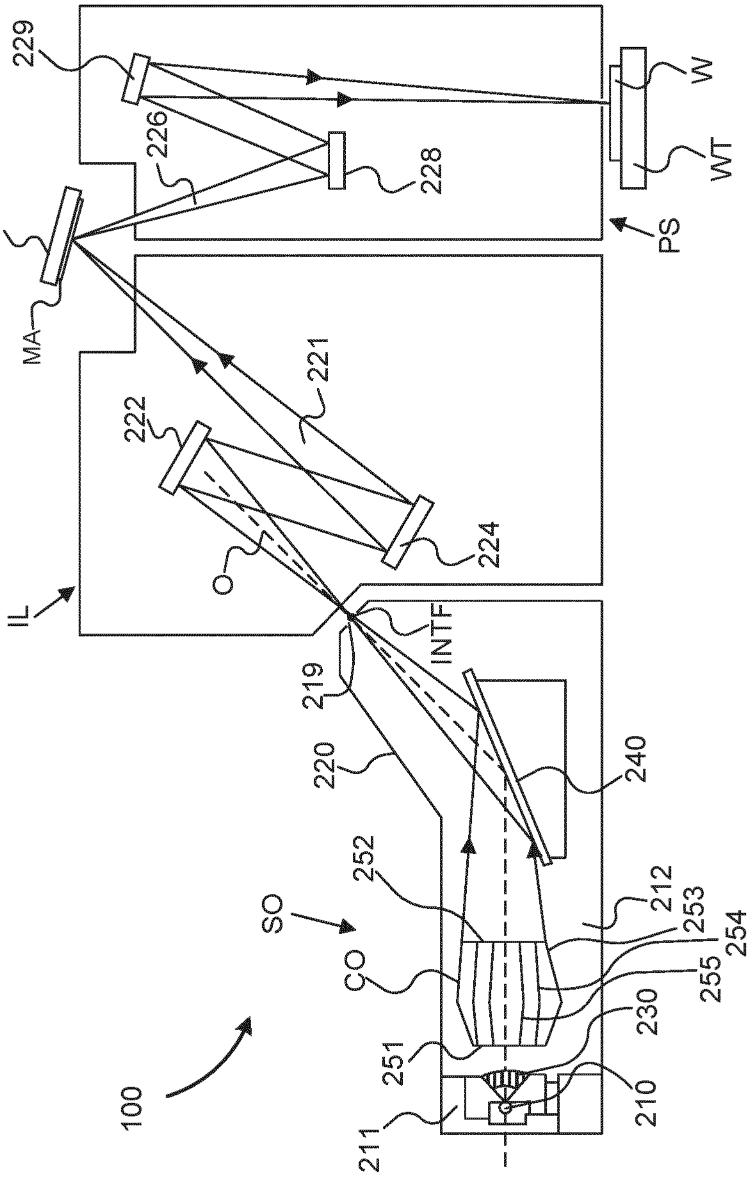
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FIG. 2

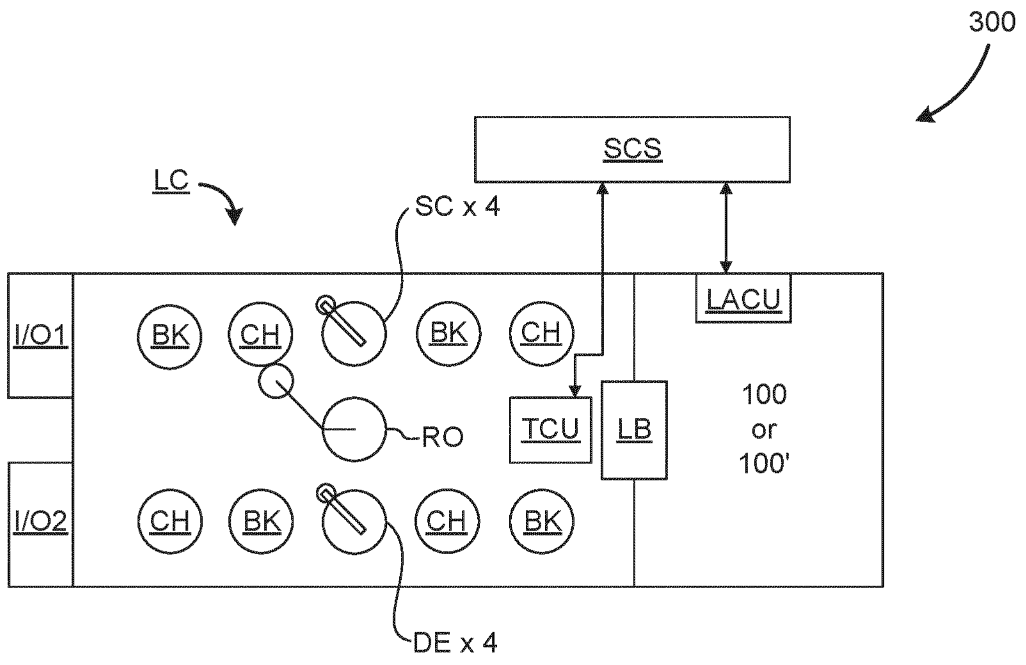
300
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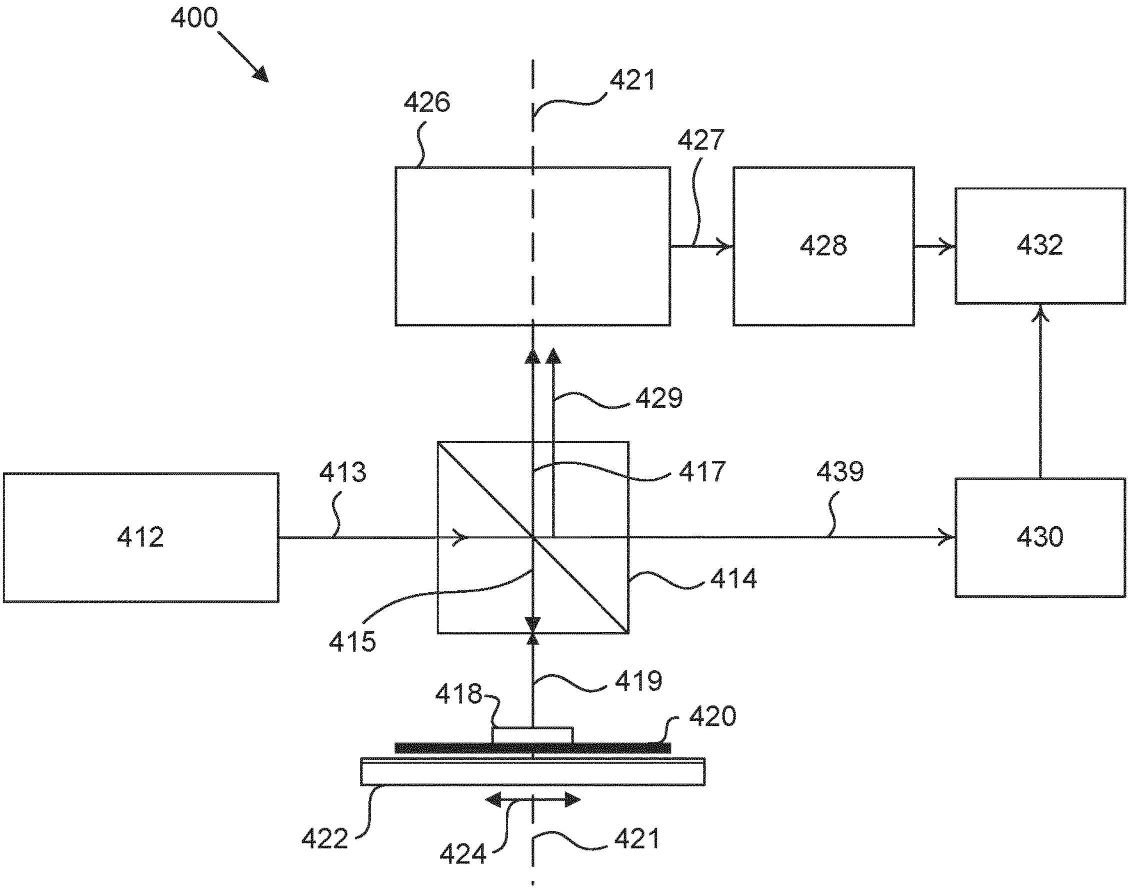
FIG. 3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420
422
424
421

FIG. 4A

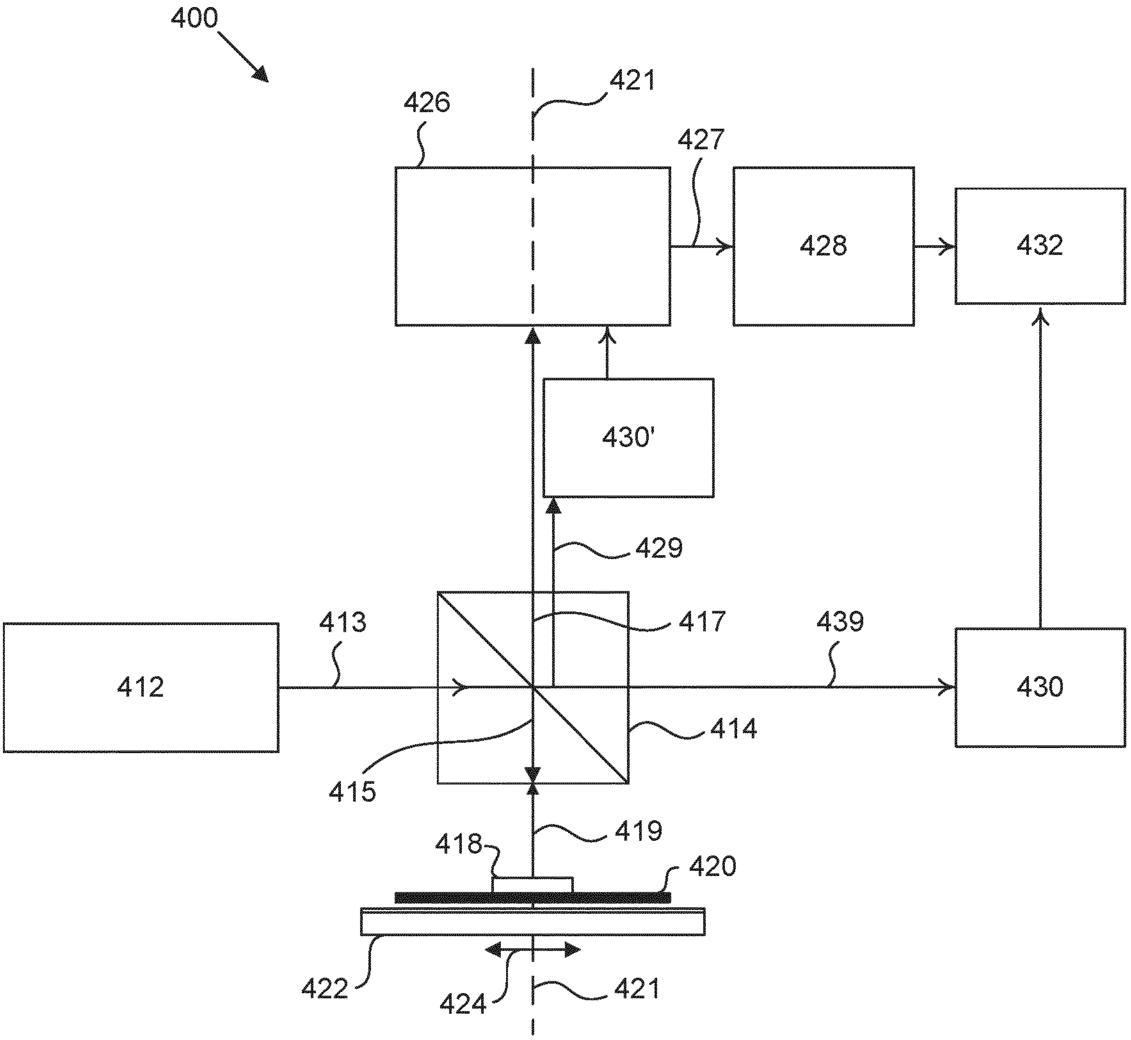
400
421
426
427
428
432
430'
429
412
413
417
439
430
415
414
419
418
420
422
424
421

FIG. 4B

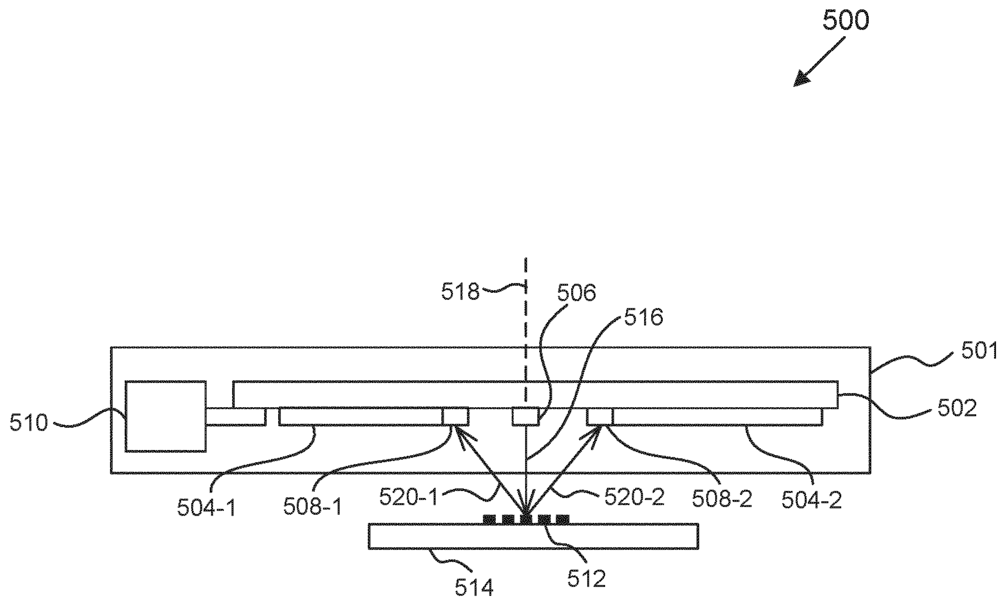
500
518
506
516
501
510
502
504-1
508-1
520-1
520-2
508-2
504-2
514
512

FIG. 5

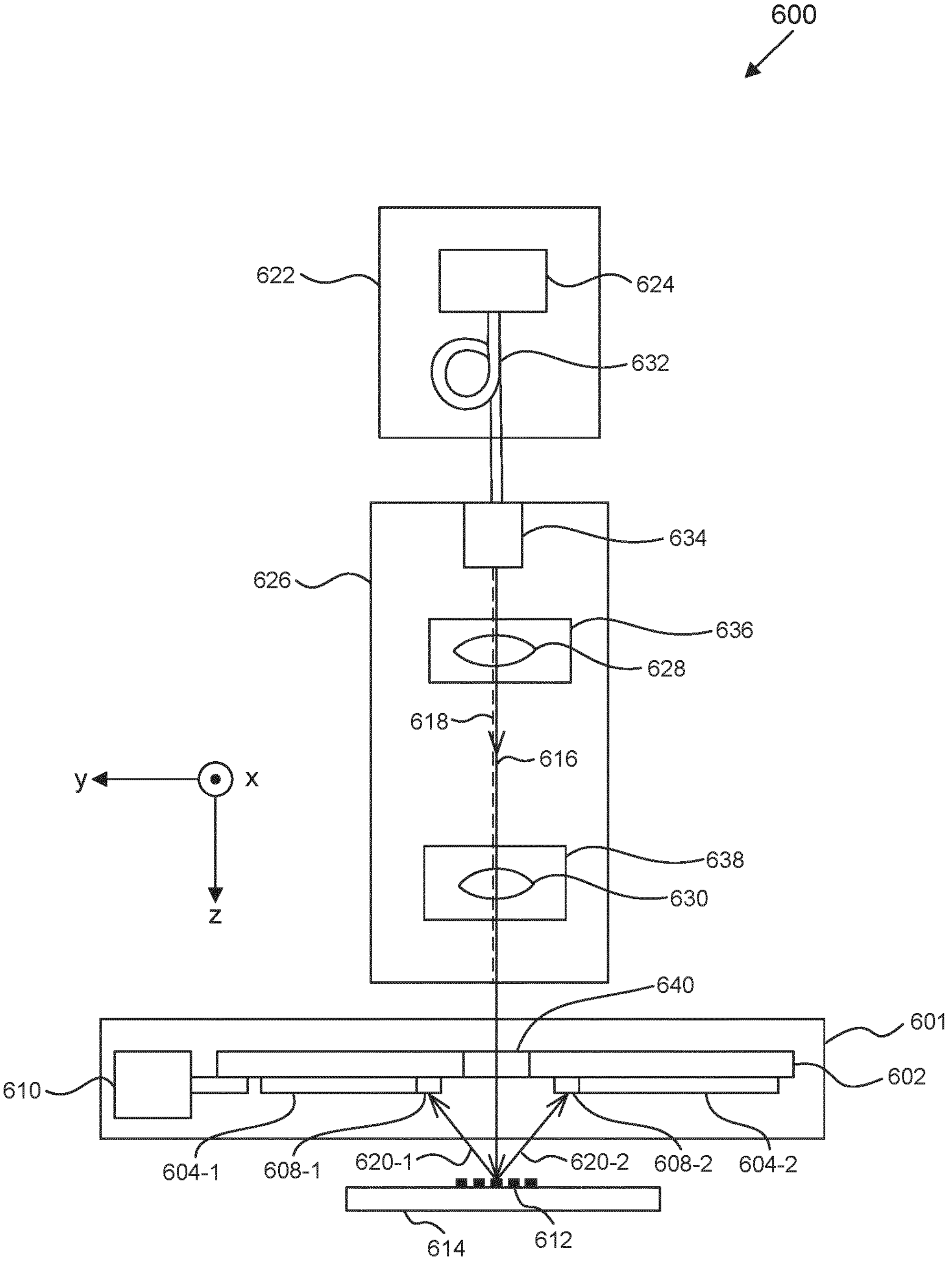
600
622
624
632
634
626
636
628
618
616
y
x
z
638
630
640
601
602
610
604-1
608-1
620-1
620-2
608-2
604-2
614
612

FIG. 6

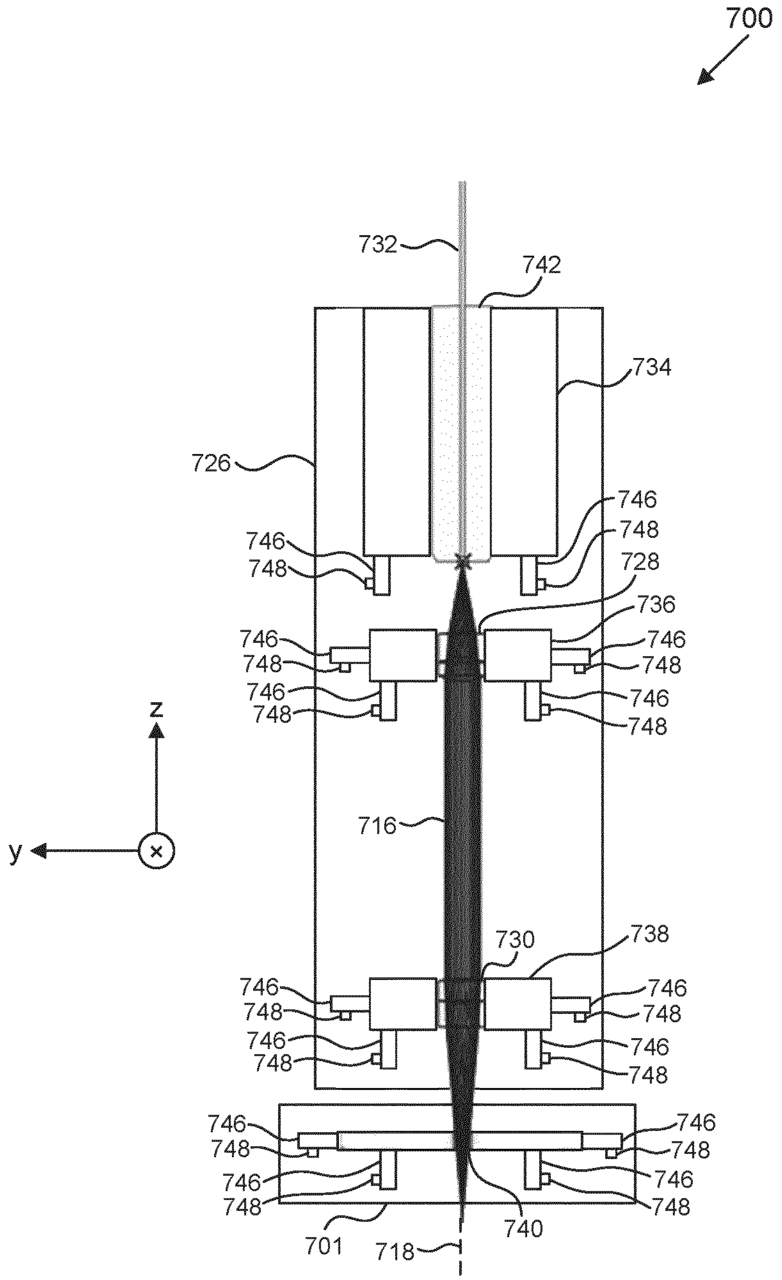

FIG. 7A

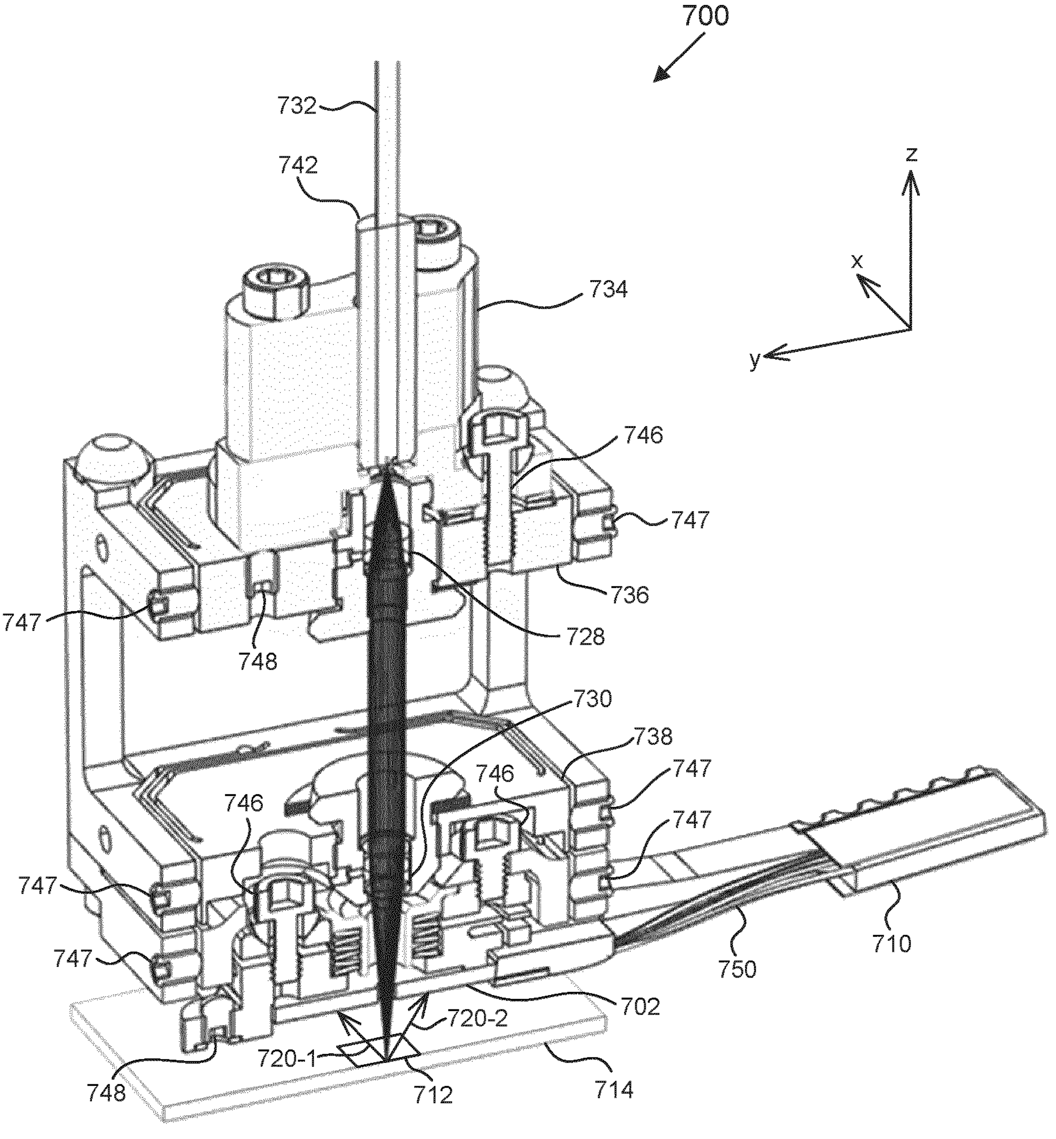
700
732
742
734
z
x
y
746
747
747
736
748
728
730
738
746
747
746
747
747
747
750
710
702
720-2
720-1
748
712
714

FIG. 7B

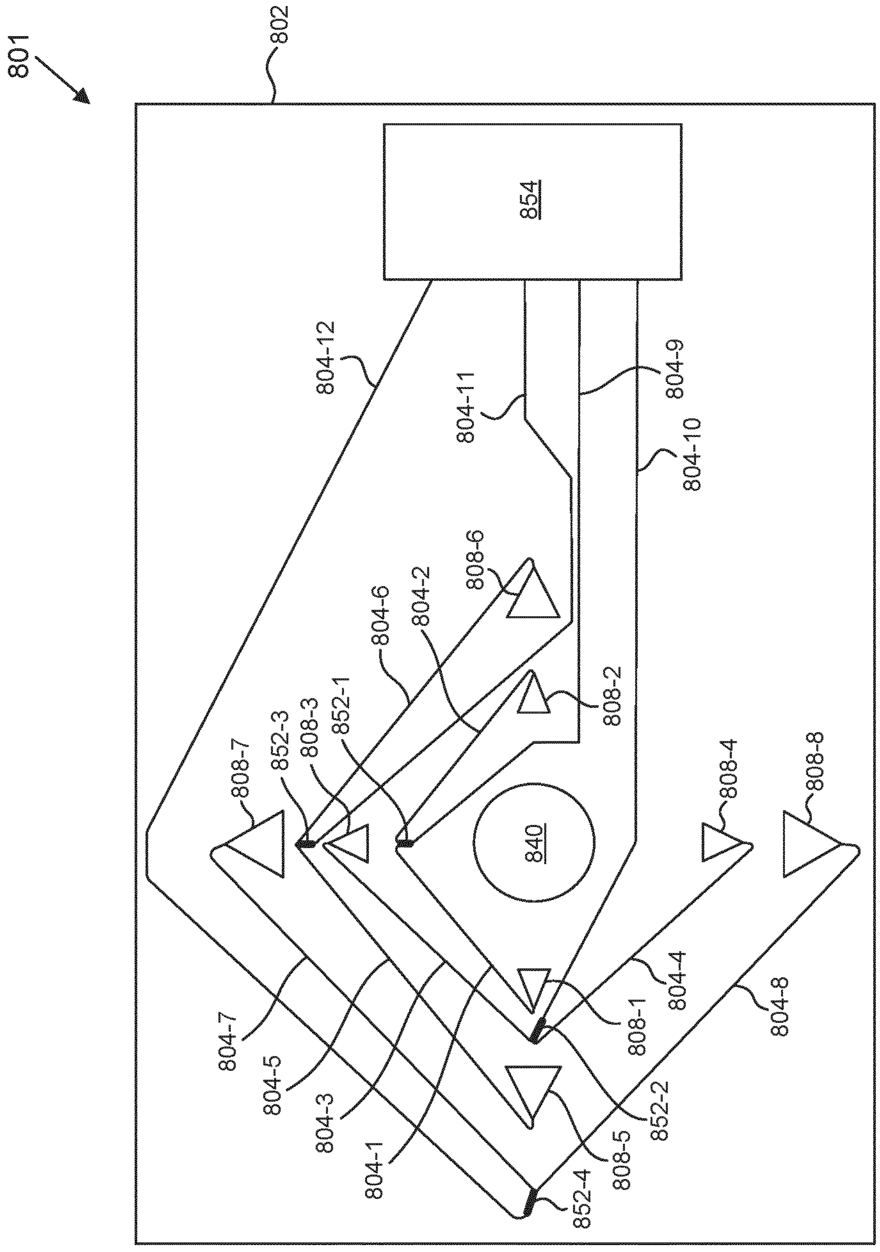
801
802
854
804-12
804-11
804-9
804-10
808-6
804-6
804-2
808-2
808-7
852-3
808-3
852-1
840
808-4
808-8
804-4
808-1
804-8
804-7
804-5
804-3
804-1
852-2
808-5
852-4

FIG. 8

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2024/063865

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims;; it is covered by claims Nos.:
1-3, 7-12

**Remark on Protest**

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
☐ No protest accompanied the payment of additional search fees.

# INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2024/063865

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. G03F7/00 G01M11/00 G01N21/95 G01N21/956 G02B6/124 G03F9/00

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 G02B G01N G01M

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

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | WO 2022/258275 A1 (ASML NETHERLANDS BV [NL]) 15 December 2022 (2022-12-15)<br>paragraph [0096]<br>paragraph [0113]<br>paragraphs [0105] - [0114]; figures 1B, 5A<br>paragraphs [0147] - [0162]; figures 9A,9B<br>----- | 1,3,<br>7-10,12 |

-/--

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

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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<br>8 August 2024 | Date of mailing of the international search report<br>18/10/2024 |
| Name and mailing address of the ISA/<br>European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Authorized officer<br>van Toledo, Wiebo |

1

C(Continuation). **DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | "INSPECTION SYSTEMS USING METASURFACE AND INTEGRATED OPTICAL SYSTEMS FOR LITHOGRAPHY",<br>RESEARCH DISCLOSURE, KENNETH MASON PUBLICATIONS, HAMPSHIRE, UK, GB<br>,<br>vol. 705, no. 8<br>1 November 2022 (2022-11-01), XP007150816,<br>ISSN: 0374-4353<br>Retrieved from the Internet:<br>URL:https://www.researchdisclosure.com/database/RD705008<br>[retrieved on 2022-11-25]<br>paragraphs [0054] - [0057]; figures 1B, 4A<br>paragraph [0070]<br>paragraphs [0076] - [0086]; figure 5<br>----- | 1,2,8,<br>10,11 |
| A | US 2014/055788 A1 (DEN BOEF ARIE JEFFREY MARIA [NL] ET AL)<br>27 February 2014 (2014-02-27)<br>paragraphs [0089] - [0093]; figures 1,5<br>----- | 1,10 |
| A | US 2018/335365 A1 (KAMEI SHIN [JP] ET AL)<br>22 November 2018 (2018-11-22)<br>paragraph [0091]<br>paragraphs [0117] - [0121]<br>----- | 10-12 |

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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2024/063865

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
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| | | SG 11201804105R A | 28-06-2018 |
| | | US 2018335365 A1 | 22-11-2018 |
| | | WO 2017085934 A1 | 26-05-2017 |

**FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210**

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-3, 7-12

   Inspection system having increased analysis versatility

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2. claims: 4-6, 13-15

   Inspection system having improved optical performance

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