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(54) **Title:** APPARATUS FOR AND METHOD OF WAVELENGTH CONTROL FOR MULTIFOCAL IMAGING

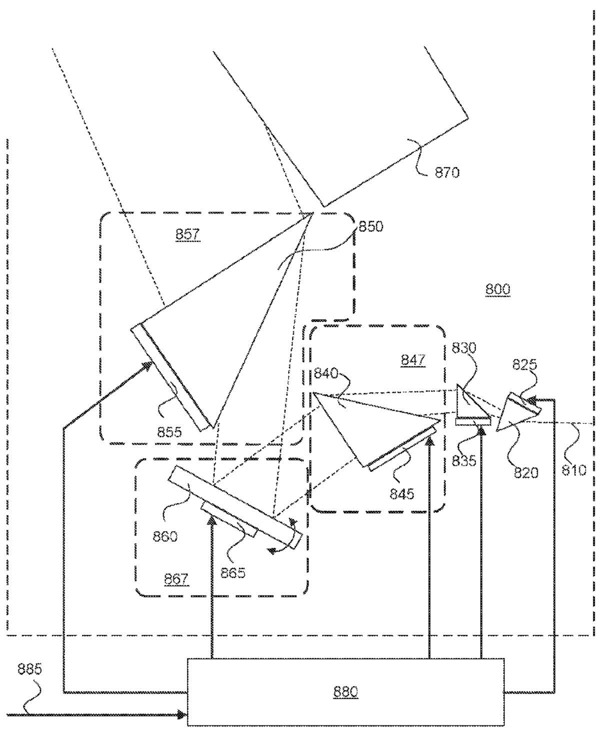

FIG. 8

(57) **Abstract:** Apparatus for and methods of performing multifocal imaging in a semiconductor lithography system in which a wavelength switching assembly is interposed in an optical path for laser radiation between a fine wavelength control assembly and a coarse wavelength control assembly to alter an angle of incidence of the laser radiation on a diffraction grating.

[Continued on next page]

WO 2025/133752 A1

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APPARATUS FOR AND METHOD OF WAVELENGTH CONTROL FOR MULTIFOCAL IMAGING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to US Application No. 63/613,215, filed December 21, 2023, titled APPARATUS FOR AND METHOD OF WAVELENGTH CONTROL FOR MULTIFOCAL IMAGING, which is incorporated herein by reference in its entirety.

FIELD

[0002] The present disclosure relates to laser systems such as excimer lasers that produce laser radiation and systems and methods for controlling the wavelength of the laser radiation.

BACKGROUND

[0003] A lithographic apparatus applies a desired pattern onto a substrate such as a wafer of semiconductor material, usually onto a target portion of the substrate. A patterning device, which may be a mask or a reticle, may be used to generate a circuit pattern to be formed on an individual layer of the wafer. Transfer of the pattern is typically accomplished by imaging onto a layer of radiation-sensitive material (resist) provided on the substrate. In general, a single substrate will contain adjacent target portions that are successively patterned.

[0004] Lithographic apparatus 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 substrate parallel or antiparallel to this direction. It is also possible to transfer the pattern from the patterning device to the substrate by imprinting the pattern onto the substrate.

[0005] The light source used to illuminate the pattern and project it onto the substrate can be of any one of a number of configurations. Deep ultraviolet (DUV) excimer lasers commonly used in lithography systems include the krypton fluoride (KrF) laser producing laser radiation having a center wavelength at 248 nm wavelength and the argon fluoride (ArF) laser producing laser radiation having a center wavelength at 193 nm wavelength. Laser radiation at such wavelengths is referred to as "light" herein even though these wavelengths are shorter than those of the visible part of the spectrum.

[0006] The lithographic apparatus may operate at a single wavelength in what may be referred to as a single-color mode or single focus imaging (SFI). For some applications, however, it is desired to have the ability to change wavelength, that is, to operate in a multicolor mode to control the depth of focus (DoF) of the laser beam. For example, in the fabrication of 3D NAND memory, structures resembling NAND gates are stacked on top of each other, extending the fabrication in a third dimension orthogonal to the x-y plane of the 2D substrate. The transition from 2D to 3D NAND architecture requires significant changes in manufacturing processes including a need for a greater DoF. Lithography DoF is determined by the relationship DoF = $\pm$ m2 $\lambda/(NA)^2$ where λ is the wavelength of the illuminating light, NA is the numerical aperture, and m2 is a practical factor depending on the resist process. Due to greater DoF requirements in 3D NAND lithography, sometimes more than one exposure pass is made over a wafer using a different laser wavelength for each pass.

[0007] As opposed to SFI, multifocal imaging (MFI) uses multiple focus levels (e.g., via multiple wavelengths focusing at different depths) to effectively increase DoF for a given NA of the objective lens. The materials making up the lenses that focus the laser radiation are dispersive, so different wavelengths come to focus at different depths. This technique can be tuned specifically to provide the required amount of wavelength separation (peak separation) for a specific DoF need. This enables the imaging NA, and therefore exposure latitude (process window), to be increased while the DoF can be optimized by MFI in accordance with production layer needs.

[0008] As described in more detail below, in the DUV laser systems under consideration here, an optical train made up of a series of modules conditions the pulses while conveying them from where they are generated to where they are used. One module in the optical train is a line narrowing module (LNM). The LNM is comprised of a diffractive grating element that acts as a wavelength-selective reflector, and includes optical prisms that refract the laser beam to adjust the angle of incidence and dispersion of light onto the grating, thus controlling both wavelength and bandwidth. In other words, within the LNM the laser radiation is reflected by a grating at a given angle to control the center wavelength and other spectral properties such as bandwidth or linewidth of the laser radiation. Each prism in a series of prisms positioned in the LNM is coupled to a respective electro-actuatable element (EAE) that controls the position and/or orientation of the prism which in turn affects the incidence angle of the laser radiation on the grating. The prisms may be beam-expanding prisms.

[0009] In DUV laser systems operating in a single-color mode, two EAEs work in conjunction with one another to control stabilization of the center wavelength. In operation, one EAE such as a stepper motor is used which has limited resolution, and a secondary EAE such as a piezoelectric transducer (PZT) is used as the primary actuator for fine wavelength control. However, in a two-color mode, wavelength stability is based on a central or peak wavelength, i.e., a mean of two alternating peaks, and in this mode, an oscillating prism inside the LNM provides a wavelength shift that is synchronized with the laser firing to produce laser pulses with the output wavelength alternating between two values. In such an arrangement, the secondary EAE is tasked with the production of the waveform that generates the alternating wavelengths. This capability is enabled in some systems by repurposing the optics used for fine wavelength control so that such systems lose the capacity for fine wavelength control when operating in a two-color mode for two level MFI.

[0010] One challenge in the performance of a system such as that just described is that the EAE attached to the prism responsible for wavelength shifting has a limited range of travel. This in turn imposes a limit on the achievable amount of wavelength shift, that is, the difference in wavelength between the two output wavelengths, which is referred to as wavelength peak separation. As noted, such systems offer only a limited ability to control the wavelength resulting in reduced wavelength stability. Such systems also have inherently low efficiency due to inherent inefficiencies in the LNM which limit laser output power (laser energy per pulse).

[0011] It is in this context that the need for the subject matter disclosed herein arises.

SUMMARY

[0012] The following presents a succinct summary of one or more embodiments in order to provide a basic understanding of the embodiments. This summary is not an extensive overview of all contemplated embodiments. It is not intended to identify any elements of embodiments as being key or critical elements nor delineate the scope of any embodiments. Its sole purpose is to present some concepts of the embodiments in a concise form as a prelude to the more detailed description that is presented later.

[0013] According to an aspect of an embodiment there may be disclosed an apparatus comprising a first wavelength control assembly arranged to receive and refract laser radiation, a wavelength switching assembly arranged to receive the laser radiation refracted by the first wavelength control assembly, the wavelength switching assembly having a first state in which the wavelength switching assembly deflects the laser radiation by a first amount and a second state in which the wavelength switching assembly deflects the laser radiation by a second amount different from the first amount, and a second wavelength control assembly arranged to receive and refract laser radiation deflected by the wavelength switching assembly, the laser radiation refracted by the second wavelength control assembly being directed towards a diffraction grating with a wavelength of the laser radiation diffracted by the diffraction grating being dependent on an angle of incidence of the laser radiation on the diffraction grating.

[0014] The first wavelength control assembly may be a fine wavelength control assembly and the second wavelength control assembly may be a coarse wavelength control assembly. The first wavelength control assembly may be a coarse wavelength control assembly and the second wavelength control assembly may comprise a fine wavelength control assembly. The first wavelength control assembly may comprise at least one prism. The second wavelength control assembly may comprise at least one prism.

[0015] The wavelength switching assembly may comprise a mirror. The mirror may comprise a plane mirror.

[0016] The wavelength switching assembly may correspond to a first angular position of the mirror and the second state of the wavelength switching assembly may correspond to a second angular position of the mirror different from the first angular position.

[0017] The apparatus may further comprise an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in

response to a control signal. The apparatus may further comprise a controller adapted to generate the control signal.

[0018] The laser radiation may be fired in one or more bursts, each burst being made up of a plurality of pulses, and the first state the wavelength switching assembly may cause a primary wavelength of some of the pulses to assume a first value and in the second state may cause others of the pulses to assume a second value different from the first value by a target primary wavelength separation amount.

[0019] The wavelength switching assembly may comprise a mirror and the first state of the wavelength switching assembly may correspond to a first angular position of the mirror and the second state of the wavelength switching assembly may correspond to a second angular position of the mirror different from the first angular position. The wavelength switching assembly may comprise an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal.

[0020] The apparatus may further comprise a controller adapted to generate the control signal. The controller may be configured to cause the wavelength switching assembly to cause the primary wavelength of the pulses to alternate between the first value and the second value on a pulse-by-pulse basis.

[0021] According to another aspect of an embodiment there is disclosed a method comprising performing a first wavelength control operation on a pulse of laser radiation by refracting the pulse of laser radiation using at least one first wavelength control prism to produce a refracted pulse of laser radiation, deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation, performing a second wavelength control operation on the deflected pulse of laser radiation by refracting the deflected pulse of laser radiation using at least one prism to produce an additionally refracted pulse of laser radiation, and diffracting the additionally refracted pulse of laser radiation using a diffraction grating to produce a diffracted pulse of laser radiation, with a wavelength of the diffracted pulse of laser radiation being dependent on an angle of incidence of the additionally refracted laser radiation on the diffraction grating.

[0022] The first wavelength control operation may be a fine wavelength control operation and the second wavelength control operation may be a coarse wavelength control operation. The first wavelength control operation may be a coarse wavelength control operation and the second wavelength control operation may be a fine wavelength control operation.

[0023] Deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation may comprise causing the refracted pulse of laser radiation to impinge upon a mirror and controlling the mirror to be in one of a first angular position or a second angular position of the mirror different from the first angular position. Controlling the mirror to be in one of a first angular position or a second angular position of the mirror different from the first angular position further may comprise controlling an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal. The method may further comprise generating the control signal.

[0024] According to another aspect of an embodiment there is disclosed a method of generating laser output at a first wavelength or at a second wavelength, the method comprising generating laser radiation at a wavelength having a base wavelength value, and controlling a mirror actuator to adjust a mirror angle of a mirror to shift a value of the wavelength of the laser radiation to dither between a first wavelength value and a second wavelength value.

[0025] The method may further comprise controlling a prism actuator to adjust a prism angle of a first prism to adjust the wavelength of the laser radiation. The mirror may be located along an optical path between the first prism and a second prism, the method further comprising controlling a second prism actuator to adjust a second prism angle of the second prism to adjust the wavelength of the laser radiation more coarsely than the adjustment by the first prism.

[0026] According to another aspect of an embodiment there is disclosed an apparatus comprising a diffraction grating in an optical path of a beam of laser radiation, a first prism in the optical path of the beam of laser radiation and moveable to adjust an angle of incidence of the beam of laser radiation on the diffraction grating, a second prism in the optical path of the beam of laser radiation and moveable to adjust an angle of incidence of the beam of laser radiation on the diffraction grating, and a mirror interposed in the optical path of the beam of laser radiation between the first prism and the second prism and rotatable between a first position which selects a first angle of incidence of the beam of laser radiation on the diffraction grating and a second position which selects a second angle of incidence of the beam of laser radiation on the diffraction grating.

[0027] The first prism may be moveable to finely adjust the angle of incidence of the beam of laser radiation on the diffraction grating and the second prism may be moveable to coarsely adjust an angle of incidence of the beam of laser radiation on the diffraction grating. The first prism may be moveable to coarsely adjust the angle of incidence of the beam of laser radiation on the diffraction grating and the second prism may be moveable to finely adjust an angle of incidence of the beam of laser radiation on the diffraction grating.

[0028] The apparatus may further comprise a controller configured to move the first and second prisms based on feedback from a center wavelength detector that detects a center wavelength of the laser radiation. The controller may be configured to move the first and second prisms on a pulse-to-pulse basis.

[0029] The first and second prisms may be beam expanding prisms.

[0030] According to another aspect of an embodiment there is disclosed a method comprising oscillating a rotational position of a mirror to change an angle of incidence of pulses of laser radiation on a grating on a pulse-by-pulse basis and so to change a wavelength of the laser radiation between two set points pulse-by-pulse, controlling a first prism to perform a first adjustment of the angle of incidence of the laser radiation on the grating, and controlling a second prism to perform a second adjustment of the angle of incidence of the laser radiation on the grating.

[0031] The first adjustment may be a fine adjustment and the second adjustment may be a coarse adjustment. The first adjustment may be a coarse adjustment and the second adjustment may be a fine adjustment.

[0032] According to another aspect of an embodiment there is disclosed a non-transitory computer-readable medium storing instructions that, when executed by a processor, cause the processor to perform operations, the operations comprising performing a first wavelength control on a pulse of laser radiation by refracting the pulse of laser radiation using at least one first wavelength control prism to produce a refracted pulse of laser radiation, deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation, performing a second wavelength control on the deflected pulse of laser radiation by refracting the deflected pulse of laser radiation using at least one second prism to produce an additionally refracted pulse of laser radiation, and diffracting the additionally refracted pulse of laser radiation using a diffraction grating to produce a diffracted pulse of laser radiation, with a wavelength of the diffracted pulse of laser radiation being dependent on an angle of incidence of the additionally refracted laser radiation on the diffraction grating.

[0033] Further features and exemplary aspects of the embodiments, as well as the structure and operation of various embodiments, are described in detail below with reference to the accompanying drawings. It is noted that the scope of all possible embodiments is not limited to the specific embodiments described herein. Such specific embodiments are presented herein for illustrative purposes only. Additional embodiments will be apparent to persons skilled in the relevant art(s) based on the teachings contained herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] The accompanying drawings, which are incorporated herein and form part of the specification, illustrate the embodiments and, together with the description, further serve to explain the principles of the embodiments and to enable a person skilled in the relevant art(s) to make and use the embodiments.

[0035] FIGS. 1A, 1B, and 1C are a schematic illustrations of a lithographic apparatus, according to an exemplary embodiment.

[0036] FIG. 2A is a schematic illustration of a light source apparatus, according to an exemplary embodiment.

[0037] FIG. 2B is a schematic illustration of a spectral feature actuation system according to an exemplary embodiment.

[0038] FIG. 2C is a schematic cross-sectional illustration of a line narrowing module according to an exemplary embodiment.

[0039] FIGS. 3A – 3C are diagrams of a laser burst made up of laser pulses illustrating certain principles underlying operation of an aspect of an embodiment.

[0040] FIG. 4 is a conceptual schematic of a photolithography system according to an aspect of an embodiment.

[0041] FIG. 5 is a graph of the single-peaked optical spectrum of laser radiation produced according to an aspect of an embodiment.

[0042] FIG. 6 is a graph of the double-peaked optical spectrum of laser radiation produced according to an aspect of an embodiment.

[0043] FIG. 7A shows an example of a wavelength shifted optical spectrum according to an aspect of an embodiment.

[0044] FIG. 7B is a plot of pulse-to-pulse wavelength versus pulse number according to an aspect of an embodiment.

[0045] FIG. 8 is a diagram of system for performing wavelength adjustment and shifting for MFI according to an aspect of an embodiment.

[0046] FIG. 9 is a flow chart for a process for performing wavelength adjustment and shifting for MFI according to an aspect of an embodiment.

[0047] FIG. 10 is a functional block diagram of a computer control system for controlling a system and/or performance of a method for performing wavelength adjustment and shifting for MFI according to an aspect of an embodiment.

[0048] The features and exemplary aspects of the embodiments will become more apparent from the detailed description set forth below when taken in conjunction with the drawings. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. Unless otherwise indicated, the drawings should not be interpreted as to-scale drawings.

DETAILED DESCRIPTION

[0049] The embodiments described, and references in the specification to "one embodiment," "an embodiment," "an exemplary embodiment," "an example embodiment," etc., indicate that the embodiments described may include a particular feature, structure, or characteristic, but not every embodiment necessarily includes the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is understood that it is within the knowledge of one skilled in the art to effect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

[0050] Spatially relative terms may be used herein for ease of description to describe one element or feature's relationship to another element or feature 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 may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

[0051] The term "about" or "substantially" or "approximately" as used herein indicates the value of a given quantity that can vary based on a particular technology. Based on the particular implementation, the term "about" or "substantially" or "approximately" can indicate a value of a given quantity that varies within, for example, 1–15% of the value (e.g., ±1%, ±2%, ±5%, ±10%, or ±15% of the value).

[0052] Embodiments of the disclosure may be implemented in hardware, firmware, software, or any combination thereof. Embodiments of the disclosure may also be implemented as instructions stored on a tangible machine-readable medium, which may be read and executed by one or more processors. A machine-readable medium may include 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 may include 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. Further, firmware, software, routines, and/or instructions may be described herein as performing certain actions. However, it should be appreciated that such descriptions are merely for convenience and that such actions in fact result from computing devices, processors, controllers, or other devices executing the firmware, software, routines, instructions, etc.

[0053] Before describing such embodiments in more detail, it is useful to present an example environment in which embodiments of the present disclosure may be implemented.

[0054] Referring to FIG. 1A, a photolithography system 100 includes a light source 105 that provides a light beam 160 to a lithography exposure apparatus 169, which processes a wafer 170 received by a wafer holder or stage 171. The light beam 160 is a pulsed light beam that includes pulses of light separated from each other in time. The lithography exposure apparatus 169 includes a projection optical system 175 through which the light beam 160 passes prior to reaching the wafer 170, and a metrology system 172. The metrology system 172 may include, for example, a camera or other device that is able to capture an image of the wafer 170 and/or the light beam 160 at the wafer 170, or an optical detector that is able to capture data that describes characteristics of the light beam 160, such as intensity of the light beam 160 at the wafer 170 in the x-y plane. The lithography exposure apparatus 169 can be a liquid immersion system or a dry system. The photolithography system 100 also may include a control system 150 to control the light source 105 and/or the lithography exposure apparatus 169. As shown, in some embodiments the control system may receive a metrology signal 151 from the metrology system 172 indicating the results of a measurement performed by the metrology system 172. The control system may use the signal 150 to develop a control signal 152 to control the light source 105 and/or the lithography exposure apparatus 169.

[0055] Microelectronic features are formed on the wafer 170 by, for example, exposing a layer of radiation-sensitive photoresist material on the wafer 170 with the light beam 160. Referring also to FIG. 1B, the projection optical system 175 includes a slit 176, a mask 174, and a projection objective, which includes a lens 177. The light beam 160 enters the optical system 175 and impinges on the slit

176, and at least some of the beam 160 passes through the slit 176. In the example of FIGS. 1A and 1B, the slit 176 is rectangular and causes the cross section of the light beam 160 to assume an elongated rectangular shape. A pattern is formed on the mask 174. The pattern determines which portions of the shaped light beam are transmitted by the mask 174 and which are blocked by the mask 174. The design of the pattern is determined by the specific microelectronic circuit design that is to be formed on the wafer 170.

[0056] The shaped light beam interacts with the mask 174. The portions of the shaped light beam that are transmitted by the mask 174 pass through (and may be focused by) the projection lens 177 and expose the wafer 170. The portions of the shaped light beam that are transmitted by the mask 174 form an aerial image in the x-y plane in the wafer 170. The aerial image is the intensity pattern formed by the light that reaches the wafer 170 after interacting with the mask 174.

[0057] The system 100 is able to form a plurality of aerial images during a single exposure pass, with each of the aerial images being at a spatially distinct location along the z axis in the wafer 170. Referring also to FIG. 1C, which shows a cross-sectional view of the wafer 170 in the y-z plane, the projection optical system 175 forms two aerial images 173a, 173b at different planes along the z axis in a single exposure pass. As described in greater detail below, one of the aerial images 173a, 173b is formed from light having a first primary wavelength and the other of aerial images 173a, 173b is formed from light having a second primary wavelength different from the first primary wavelength.

[0058] The location of the aerial image along the z axis depends on the characteristics of the optical system 175 (including the projection lens 177 and the mask 174) and the wavelength of the light beam 160. The focal position of the lens 177 depends on the wavelength of the light incident on the lens 177. Thus, varying or otherwise controlling the wavelength of the light beam 160 controls the position of the aerial image. By providing pulses having differing primary wavelengths of light during a single exposure pass, a plurality (two or more) of aerial images, which are each at a different location along the z axis, may be formed in a single exposure pass without physically moving the optical system 175 (or any components of the optical system 175) and the wafer 170 relative to each other along the z axis.

[0059] In the example of FIG. 1B, light passing through the mask 174 is focused to a focal plane by the projection lens 177. The focal plane of the projection lens 177 is between the projection lens 177 and the wafer stage 171, with the position of the focal plane along the z axis depending on the properties of the optical system 175 and the wavelength of the light beam 160. The aerial images 173a, 173b are respectively formed from light having different wavelengths, thus the aerial images 173a, 173b are at different locations (depths) in the wafer 170. The aerial images 173a, 173b are separated from each other along the z axis by a separation distance 179. The separation distance 179 depends on the difference between the wavelength of the light that forms the aerial image 173a and the wavelength of the light that forms the aerial image 173b.

[0060] The separation distance 179 arises due to the ability to control the primary wavelengths in the pulses that pass through the mask 174 during the exposure pass. Moreover, the aerial images 173a and 173b are both present at the wafer 170 during the same exposure pass. In other words, the system 100 does not require that the aerial image 173a be formed in a first exposure pass and the aerial image 173b be formed in a second, subsequent exposure pass.

[0061] The light in the first aerial image 173a interacts with the wafer at a depth 178a, and the light in the second aerial image 173b interacts with the wafer at a depth 178b. These interactions may form electronic features or other physical characteristics, such as openings or holes, on the wafer 170. Because the aerial images 173a and 173b are formed at positions that are displaced along the z axis, forming the aerial images 173a and 173b may be carried out as part of a process to fabricate three-dimensional features on the wafer 170. For example, the aerial image 173a may be used to form a periphery region, and the aerial image 173b may be used to form a channel, trench, or recess that is at a different location along the z axis. As such, the techniques discussed herein may be used to form a three-dimensional semiconductor component, such as a three-dimensional NAND flash memory component.

[0062] Before discussing additional details related to forming multiple aerial images in a single exposure pass, example implementations of the light source 105 and the photolithography system 100 are described with respect to FIGS. 2A-2C, 3A-3C, and 4.

[0063] Referring to FIG. 2A, a block diagram of a photolithography system 200 is shown. The system 200 is an example of an implementation of the system 100 (FIG. 1A). For example, in the photolithography system 200, an optical source 205 is used as the optical source 105 (FIG. 1A). The optical source 205 produces a pulsed light beam 260, which is provided to the lithography exposure apparatus 169. The optical source 205 may be, for example, an excimer optical source that outputs the pulsed light beam 260. As the pulsed light beam 260 enters the lithography exposure apparatus 169, it is directed through the projection optical system 175 and projected onto the wafer 170. In this way, one or more microelectronic features are patterned onto a photoresist on the wafer 170 that is then developed and cleaned prior to subsequent process steps, and the process repeats. The photolithography system 200 also includes a control system 250, which, in the example of FIG. 2A, is connected to components of the optical source 205 as well as to the lithography exposure apparatus 169 to control various operations of the system 200. The control system 250 is an example of an implementation of the control system 150 of FIG. 1A.

[0064] In the example shown in FIG. 2A, the optical source 205 is a two-stage laser system that includes a master oscillator (MO) 212 that provides a seed light beam 224 to a power amplifier (PA) 230. The MO 212 and the PA 230 may be considered to be subsystems of the optical source 205 or systems that are part of the optical source 205. The power amplifier 230 receives the seed light beam 224 from the master oscillator 212 and amplifies the seed light beam 224 to generate the light beam 260 for use in the lithography exposure apparatus 169. For example, the master oscillator 212 may emit a pulsed seed light beam, with seed pulse energies of approximately 1 millijoule (mJ) per pulse, and these seed pulses may be amplified by the power amplifier 230 to about 10 to 15 mJ.

[0065] The master oscillator 212 includes a discharge chamber 214 having two elongated electrodes 217, a gain medium 219 that is a gas mixture, and a fan (not shown) for circulating gas between the electrodes 217. A resonator is formed by an LNM 216 on one side of the discharge chamber 214 and an output coupler 218 on an opposite side of the discharge chamber 214. As described above, the LNM 216 may include a diffractive optic such as a grating that finely tunes and shifts the spectral output of the discharge chamber 214.

[0066] FIGS. 2B and 2C provide additional details about the LNM 216. FIG. 2B is a block diagram of an example of an implementation of a spectral feature selection module 258. The spectral feature selection module 258 couples to light that propagates in the optical source 205. In some implementations (such as that shown in FIG. 2B), the spectral feature selection module 258 receives the light from the chamber 214 of the master oscillator 212 to enable fine tuning of spectral features such as wavelength and bandwidth within the master oscillator 212.

[0067] The spectral feature selection module 258 may include a control module such as a spectral feature control module 254 that includes electronics in the form of any combination of firmware and software. The control module 254 is connected to one or more actuation systems such as spectral feature actuation systems 255_1 to 255_n. Each of the actuation systems 255_1 to 255_n may include one or more actuators that are connected to respective optical features 256_1 to 256_n of an optical system 257.

[0068] The optical features 256_1 to 256_n are configured to adjust spectral features of the light beam 260. The control module 254 receives a control signal from the control system 250, the control signal including specific commands to operate or control one or more of the actuation systems 255_1 to 255_n. The actuation systems 255_1 to 255_n can be selected and designed to work together, that is, in tandem, or the actuation systems 255_1 to 255_n may be configured to work individually. Moreover, each actuation system 255_1 to 255_n may be optimized to respond to a particular class of disturbances.

[0069] Each of the actuators of the actuation systems 255_1 to 255_n may be an EAE for moving or controlling the respective optical features 256_1 to 256_n of the optical system 257. The actuators receive energy from the control module 254 and convert that energy into motion imparted to the optical features 256_1 to 256_n of the optical system 257.

[0070] Each optical feature 256_1 to 256_n is optically coupled to the light beam 260 produced by the optical source 205. The optical system 257 may be implemented as an LNM 216c such as that shown in FIG. 2C. LNM 216c includes as the optical features 256_1 to 256_n dispersive optical elements such as a reflective grating 291 and refractive optical elements such as prisms 292, 293, 294, and 295. One or more of the prisms 292, 293, 294, and 295 may be rotatable. An example of this line narrowing module can be found in U.S. Patent No. 8,144,739, titled “System Method and Apparatus for Selecting and Controlling Light Source Bandwidth”, issued March 27, 2012 (the ’739 patent). In the ’739 patent an LNM is described that includes a beam expander (including the one or more prisms 292, 293, 294, and 295) and a dispersive element such as the grating 291.

[0071] All patent applications, patents, and printed publications cited herein are incorporated herein by reference in their entireties, except for any definitions, subject matter disclaimers or disavowals, and except to the extent that the incorporated material is inconsistent with the express disclosure herein, in which case the language in this disclosure controls.

[0072] The respective actuation systems for the optical features such as one or more of the prisms 292, 293, 294, and 295 are represented in FIG. 2C by EAEs 292a, 293a, 294a, and 295a, respectively. A mirror may also be present and rotated to change the angle of incidence of the light beam on the grating 291 and so the primary wavelength of the emitted light. Each prism has an EAE that moves the prism under the command of a voltage command signal. Thus, in general, LNM 216c includes one or more optical elements that are rotated to change the primary wavelength of the light leaving the module. These EAEs must be able to move the optical elements very rapidly between two positions, usually two angular positions, in a process referred to as dithering.

[0073] Returning to FIG. 2A, the master oscillator 212 also includes a line center analysis module 220 that receives an output light beam from the output coupler 218 and a beam coupling optical system 222 that modifies the size or shape of the output light beam as needed to form the seed light beam 224. The line center analysis module 220 is a measurement system that may be used to measure or monitor the wavelength of the seed light beam 224. The line center analysis module 220 may be placed at other locations in the optical source 205, or it may be placed at the output of the optical source 205.

[0074] The power amplifier 230 includes a beam coupling optical system 232 that receives the seed light beam 224 from the master oscillator 212 and directs the seed light beam 224 through a discharge chamber 240, and to a beam turning optical element 248. The beam turning optical element 248 modifies or changes the direction of the seed light beam 224 so that it is sent back into the discharge chamber 240. The discharge chamber 240 includes a pair of elongated electrodes 241, a gain medium that is a gas mixture, and a fan (not shown) for circulating the gas mixture between the pair of electrodes 241.

[0075] The output light beam 260 is directed through a bandwidth analysis module 262, where various parameters (such as the bandwidth or the wavelength) of the beam 260 may be measured. The output light beam 260 may also be directed through a beam preparation system 263. The beam preparation system 263 may include, for example, a pulse stretcher, where each of the pulses of the output light beam 260 is stretched in time, for example, in an optical delay unit, to adjust for performance properties of the light beam that impinges on the lithography exposure apparatus 169. The beam preparation system 263 also may include other components that are able to act upon the beam 260 such as, for example, reflective and/or refractive optical elements (such as, for example, lenses and mirrors), filters, and optical apertures (including automated shutters).

[0076] The photolithography system 200 also includes the control system 250. In the implementation shown in FIG. 2A, the control system 250 is connected to various components of the optical source 205. For example, the control system 250 may control when the optical source 205 emits a pulse of light or a burst that includes one or more pulses of light by sending one or more trigger signals to the optical source 205. The control system 250 is also connected to the lithography exposure apparatus 169. Thus, the control system 250 also may control the various aspects of the lithography exposure apparatus 169. For example, the control system 250 may control the exposure of the wafer 170 and thus may be used to control how features are printed on the wafer 170. In some implementations, the control system 250 may control the scanning of the wafer 170 by controlling the motion of the slit 176 in the x-y plane (FIG. 1B). Moreover, the control system 250 may exchange data with the metrology system 172 and/or the optical system 175.

[0077] The lithography exposure apparatus 169 also may include, for example, temperature control devices (such as air conditioning devices and/or heating devices), and/or power supplies for the various electrical components. The control system 250 also may control these components. In some implementations, the control system 250 is implemented to include more than one sub-control system, with at least one sub-control system (a lithography controller) dedicated to controlling aspects of the lithography exposure apparatus 169. In these implementations, the control system 250 may be used to control aspects of the lithography exposure apparatus 169 instead of, or in addition to, using the lithography controller.

[0078] The control system 250 includes an electronic processor 251, an electronic storage 252, and an I/O interface 253. The electronic processor 251 includes one or more processors suitable for the execution of a computer program such as a general or special purpose microprocessor, and any one or more processors of any kind of digital computer. Generally, an electronic processor receives instructions and data from a read-only memory, a random access memory, or both. The electronic processor 251 may be any type of electronic processor.

[0079] The electronic storage 252 may store various recipes or process programs 259 that dictate parameters of the light beam 260 during use. For example, the electronic storage 252 may store a recipe that indicates the wavelength of each pulse in the light beam 260 for a particular exposure pass. The recipe may indicate different wavelengths for different exposure passes. The wavelength controlling techniques discussed below may be applied on a pulse-by-pulse basis. In other words, the wavelength content may be controlled for each individual pulse in an exposure pass to facilitate formation of the aerial images at the desired locations along the z axis.

[0080] The electronic storage 252 may be volatile memory, such as RAM, or non- volatile memory. In some implementations, the electronic storage 252 includes non-volatile and volatile portions or components. The electronic storage 252 may store data and information that is used in the operation of the control system 250, components of the control system 250, and/or systems controlled by the control system 250. The information may be stored in, for example, a look-up table or a database. For example, the electronic storage 252 may store data that indicates values of various properties of the beam 260 under different operating conditions and performance scenarios.

[0081] The electronic storage 252 also may store instructions, perhaps as a computer program, that, when executed, cause the processor 251 to communicate with components in the control system 250, the optical system 205, and/or the lithography exposure apparatus 169.

[0082] The I/O interface 253 is any kind of electronic interface that allows the control system 250 to receive data and signals and/or provide data and signals with an operator, the optical system 205, the lithography exposure apparatus 169, any component or system within the optical system 205 and/or the lithography exposure apparatus 169, and/or an automated process running on another electronic device. For example, the I/O interface 253 may include one or more of a visual display, a keyboard, and a communications interface.

[0083] The light beam 260 (and the light beam 160) are pulsed light beams and may include one or more bursts of pulses that are separated from each other in time. Each burst may include one or more pulses of light. In some implementations, a burst includes hundreds of pulses, for example, 100-400 pulses. FIGS. 3A-3C provide an overview of the production of pulses and bursts in the optical source 205. FIG. 3A shows an amplitude of a wafer exposure signal 300 as a function of time, FIG. 3B shows an amplitude of a gate signal 315 as a function of time, and FIG. 3C shows an amplitude of a trigger signal 330 as a function of time.

[0084] The control system 250 may be configured to send the wafer exposure signal 300 to the optical source 205 to control the optical source 205 to produce the light beam 260. In the example shown in FIG. 3A, the wafer exposure signal 300 has a high value 305 (for example, logic 1) for a period of time 307 during which the optical source 205 produces bursts of pulses of light. The wafer exposure signal 300 otherwise has a low value 310 (for example, logic 0) when the wafer 170 is not being exposed.

[0085] Referring to FIG. 3B, the control system 250 also controls the duration and frequency of the bursts of pulses by sending a gate signal 315 to the optical source 205. The gate signal 315 has a high value 320 (for example, logic 1) during a burst of pulses and a low value 325 (for example, logic 0) during the time between successive bursts. In the example shown, the duration of time at which the gate signal 315 has the high value is also the duration of a burst 316. The bursts are separated in time by an inter-burst time interval. During the inter-burst time interval, the lithography exposure apparatus 169 may position the next die on the wafer 170 for exposure.

[0086] Referring to FIG. 3C, the control system 250 also controls the repetition rate of the pulses within each burst with a trigger signal 330. The trigger signal 330 includes triggers 340 that are provided to the optical source 205 to cause the optical source 205 to produce pulses of light. The control system 250 may send a trigger 340 to the source 205 each time a pulse is to be produced. Thus, the repetition rate of the pulses produced by the optical source 205 (the reciprocal of the time between two successive pulses), or other timing of the pulses, may be set by the trigger signal 330.

[0087] As described above, when the gain medium 219 is pumped by applying voltage to the electrodes 217, the gain medium 219 emits light. When voltage is applied to the electrodes 217 in pulses, the light from the medium 219 is also emitted in pulses. Thus, the repetition rate of the pulsed light beam 260 is determined by the rate at which voltage is applied to the electrodes 217, with each application of voltage producing a pulse of light. The pulse of light propagates through the gain medium 219 and exits the chamber 214 through the output coupler 218. Thus, a train of pulses is created by periodic, repeated application of voltage to the electrodes 217. The trigger signal 330, for example, may be used to control the application of voltage to the electrodes 217 and the repetition rate of the pulses, which may range between about 500 and 6,000 Hz for most applications. In some implementations, the repetition rate may be greater than 6,000 Hz, and may be, for example, 12,000 Hz or greater

[0088] The signals from the control system 250 may also be used to control the electrodes 217, 241 within the master oscillator 212 and the power amplifier 230, respectively, for controlling the respective pulse energies of the master oscillator 212 and the power amplifier 230, and thus, the energy of the light beam 260. There may be a delay between the signal provided to the electrodes 217 and the signal provided to the electrodes 241. The amount of delay may influence properties of the beam 260, such as the amount of coherence in the pulsed light beam 260.

[0089] The pulsed light beam 260 may have an average output power in the range of tens of watts, for example, from about 50 W to about 130 W. The irradiance (that is, the average power per unit area) of the light beam 260 at the output may range from 60 W/cm^2 to 80 W/cm^2.

[0090] Referring also to FIG. 4, the wafer 170 is irradiated by the light beam 260. The lithography exposure apparatus 169 includes the optical system 175 (FIGS. 1A and 1B). In the example of FIG. 4, the optical system 175 (other parts not shown in FIG. 4) includes an illuminator system 429, which includes an objective arrangement 432. The objective arrangement 432 includes the projection lens 177 (FIG. 1B) and enables the image transfer to occur from the mask 174 to the photoresist on the wafer 170. The illuminator system 429 adjusts the range of angles for the light beam 260 impinging on the mask 174. The illuminator system 429 also may homogenize (make uniform) the intensity distribution of the light beam 260 in the x-y plane across the mask 174.

[0091] In some implementations, an immersion medium may be supplied to cover the wafer 170. The immersion medium may be a liquid (such as water) for liquid immersion lithography. In other implementations in which the lithography is a dry system, the immersion medium may be a gas such as dry nitrogen, dry air, or clean air. In other implementations, the wafer 170 may be exposed within a pressure-controlled environment (such as a vacuum or partial vacuum).

[0092] A plurality of N pulses of the light beam 260 illuminates the same area of the wafer 170. N may be any integer greater than one. The number of pulses N of the light beam 110 illuminate the same area which may be referred to as an exposure window or exposure pass 400. The size of the window 400 may be controlled by the slit 176. For example, the slit 176 may include a plurality of blades that are movable such that the blades form an aperture that is open in one configuration and closed in another configuration. By arranging the blades of the slit 176 to form an aperture of a particular size, the size of the window 400 also may be controlled.

[0093] The N pulses also determine an illumination dose for the exposure pass. The illumination dose is the amount of optical energy that is delivered to the wafer 170 during the exposure pass. Thus, the number N and the properties of the N pulses, such as the optical energy in each pulse, determine the illumination dose. Moreover, and as described in greater detail below, the N pulses also may be used to determine the amount of light in each of the aerial images 173a, 173b (FIG. 1C). In particular, a recipe may specify that a certain number of the N pulses have a first primary wavelength that forms the aerial image 173a and a certain number of the N pulses have a second primary wavelength that forms the aerial image 173b. These two types of pulses, which will have wavelengths that differ from each other, may be interspersed, for example, pulse-to-pulse or in some other manner, i.e., in alternating groups of pulses.

[0094] Additionally, the slit 176 and/or the mask 174 may move in a scanning direction in the x-y plane such that only a portion of the wafer 170 is exposed at a given time or during a particular exposure scan (or exposure pass). The size of the area on the wafer 170 exposed by the light beam 160 is determined by the distance between the blades in the non-scanning direction and by the length (distance) of the scan in the scanning direction. In some implementations, the value of N is in the tens, for example, each point on the wafer may receive light from 10-100 consecutive pulses during the scanning of the slit relative to that point. In other implementations, the value of N is greater than 100 pulses, for example, from 100-500 pulses. An exposure field 479 of the wafer 170 is the physical area of the wafer 170 that is exposed in one scan of an exposure slit or window within the lithography exposure apparatus 169.

[0095] The wafer stage 171, the mask 174, and the objective arrangement 432 are coupled to associated actuation systems to thereby form a scanning arrangement. In the scanning arrangement, one or more of the mask 174, the objective arrangement 432, and the wafer 170 (via the stage 171) may move relative to each other in the x-y plane. However, aside from incidental relative operational motion between the wafer stage 171, the mask 174, and the objective arrangement 432, these elements are not moved relative to each other along the z axis during an exposure pass.

[0096] Referring again to FIG. 2A, typically, tuning of the wavelength of the seed beam 224 and, hence, the light beam 260 takes place in the LNM 216. A typical technique used for line narrowing and tuning of lasers is to provide a window at the back of the laser's discharge cavity through which a portion of the laser beam passes into the LNM 216. There, the portion of the beam is expanded with a prism beam expander and directed to a grating which reflects a narrow selected portion of the laser's broader spectrum back into the discharge chamber where it is amplified as described in connection with LNM 216c in FIG. 2C. The laser is typically tuned by changing the angle at which the beam illuminates the grating 291 using one or more EAEs such as, for example, PZTs.

[0097] In some embodiments, the plurality of prisms 292-295 may be used to adjust the final incidence angle, and consequently, the wavelength selected. For example, prism 292 may have more control over the final incidence angle than the prism 293. That is, in some embodiments, the controller 250 uses prisms 292, 293 in a dual-stage configuration, with prism 292 being used for large jumps and to desaturate prism 293, which is used for finer changes to the final incidence angle, saturation occurring when the controller 250's output exceeds the physical limit of the actuator EAE 293a of the prism 293. Controlling prisms 292, 293 is of particular importance for MFI operations, which require more than regulation around a setpoint, and instead, require precise tracking of a sinusoid at the Nyquist frequency in addition to precise control of the center point of the sinusoid (i.e., the central wavelength).

[0098] As mentioned, MFI operations may include a two-color mode. In the two-color mode, a wavelength target may alternate between two known setpoints within a burst (e.g., every pulse, pulse-to-pulse), and an EAE which may be implemented as a PZT may be used to track, i.e. adjust the wavelength towards, the fast-changing wavelength target.

[0099] In some embodiments, a dither waveform (or sequence) can be combined with an offset for moving an actuator for prism 293. For example, the dither waveform may be an applied form of noise used to randomize quantization. The offset can be updated at an end-of-burst (EOB) and/or at a set pulse interval. In some embodiments, the EOB update can move the actuator for prism 293 to zero out the estimated center wavelength drift obtained by averaging the wavelength measurements of the entire burst. In some embodiments, the interval updates can be based on an estimation process.

[0100] Referring to FIG. 5, an optical spectrum 601A of a pulse of light 600A is shown. The pulse of light 600A has non-zero intensity within a band of wavelengths. The band of wavelengths also may be referred to as the bandwidth or linewidth of the pulse 600A.

[0101] The data graphed in FIG. 5 is the instantaneous optical spectrum 601A (or emission spectrum) of the pulse 600A. The optical spectrum 601A contains information about how the optical energy or power of a pulse of the light beam 260 is distributed over different wavelengths (or frequencies). The optical spectrum 601A is depicted in the form of a diagram where the spectral intensity (not necessarily with an absolute calibration) is plotted as a function of the wavelength. The optical spectrum 601A may be referred to as the spectral shape or intensity spectrum of a pulse of the light beam 260. The pulse 600A has a primary wavelength 602A, which, in the example of FIG. 5, is the peak intensity. Although the description of the pulses of the light beam 260 and the aerial images formed by the pulses of the light beam 260 refers to the primary wavelengths of the pulses, the pulses include wavelengths other than the primary wavelength and the pulses have a finite bandwidth that may be characterized by a metric. For example, the full width of the spectrum 601A at a fraction (X) of the maximum peak intensity of the spectral shape (referred to as FWXM) may be used to characterize the light beam bandwidth. As another example, the width of the spectrum that contains a fraction (Y) of the integrated spectral intensity (referred to as EY) may be used to characterize the light beam bandwidth. The pulse 600A is shown as an example of a pulse that may be part of the light beam 260.

[0102] The light in the pulse forms an aerial image when the pulse 600A is used to expose a portion of the wafer 170. The location of the aerial image in the z direction (FIGS. 1A-C) is determined by the value of the primary wavelength 602A. The various pulses in the light beam 260 may have primary wavelengths that differ from one another.

[0103] The light source 205 may dither or switch the primary wavelength between the first and second primary wavelengths on a burst-to-burst, pulse-to-pulse, or even an intra-pulse basis. For the pulse-to-pulse case each pulse has a different primary wavelength than a pulse that immediately precedes and a pulse that immediately follows the pulse in time. In these implementations, assuming that all of the pulses in the light beam 260 have the same intensity, distributing the first and second primary wavelengths in this manner results in two aerial images at different locations in the z direction with the same intensity.

[0104] In some implementations, a certain portion (for example, 33%) of the pulses have a first primary wavelength, and the remainder (67% in this example) have a second primary wavelength. Here and elsewhere, "first" and "second" are used merely as differentiating labels, and not temporal order, unless the context indicates otherwise. In these implementations, assuming that all of the pulses in the light beam 260 have the same intensity, two aerial images are formed of different intensities. The aerial image formed by the pulses having the first primary wavelength has about half of the intensity of the aerial image formed by the pulses having the second primary wavelength. In this way, the dose provided to a particular location in the wafer 170 along the z axis may be controlled by controlling the portion of the N pulses that have the first primary wavelength and the portion of the N pulses that have the second primary wavelength.

[0105] The portion of pulses that are to have a particular primary wavelength for an exposure pass may be specified in the recipe file 259 that is stored in the electronic storage 252 (see FIG. 2A). The recipe file 259 specifies the ratio of the various primary wavelengths for an exposure pass. The recipe file 259 also may specify the ratio for other exposure passes, such that a different ratio may be used for other exposure passes and the aerial images may be adjusted or controlled on a field-by-field basis.

[0106] Referring to FIG. 6, an optical spectrum 601B of a pulse 600B is shown. The pulse 600B is another example of pulse of the light beam 260. The optical spectrum 601B of the pulse 600B has a different shape than the optical spectrum 601A. In particular, the optical spectrum 601B has two peaks that correspond to two primary wavelengths 602B_1 and 602B_2 of the pulse 600B. The pulse 600B is part of the light beam 260. When the pulse 600B is used to expose a portion of the wafer 170, the light in the pulse forms two aerial images at different locations along the z axis on the wafer. The locations of the aerial images are determined by the wavelengths of the primary wavelengths 602B_1 and 602B_2. Thus, one goal of a control system according to an embodiment is to control the primary wavelengths toward respective target values, i.e., to cause each primary wavelength to converge to its target value and, hence, for the separation distance to achieve a target amount.

[0107] The pulses shown in FIGS. 5 and 6 may be formed by any hardware capable of forming such pulses. For example, a pulse train of pulses such as the pulse 600A may be formed using an LNM similar to the LNM 216c of FIG. 2C. As mentioned, the wavelength of the light diffracted by the grating 291 depends on the angle of the light that is incident on the grating. A mechanism to change the angle of incidence of light that interacts with the grating 291 may be used with such a line narrowing module to create a pulse train with N pulses for an exposure pass, where at least one of the N pulses has a primary wavelength that is different from the primary wavelength of another pulse of the N pulses. For example, one of the prisms 292, 293, 294, and 295 may be rotated to change the angle of light that is incident on the grating 291 on a pulse-by-pulse basis. In some implementations, the line narrowing module includes a mirror that is in the path of the beam 260 and is movable to change the angle of light that is incident on the grating 291. An example of such an implementation is discussed, for example, in U.S. Patent No. 6,192,064, titled "Narrow Band Laser with Fine Wavelength Control", issued on February 20, 2001.

[0108] Referring again to FIG. 4, a set of pulses of light is passed through the mask 174 toward the wafer 170 during a single exposure pass. As described above, N pulses of light may be provided to the wafer 170 during the exposure pass. The N pulses of light may be consecutive pulses of light in the beam 260. The exposed portion of the wafer 170 sees an average of the optical spectrum of each of the N pulses over the exposure pass. Thus, if a portion of the N pulses have a first primary wavelength and the remaining portion of the N pulses have a second primary wavelength, the average optical spectrum at the wafer 170 will be an optical spectrum that includes a peak at the first primary wavelength and a peak at the second primary wavelength. Similarly, if all or some of the individual pulses of the N pulses have more than one primary wavelength, those primary wavelengths may form peaks in the average optical spectrum.

[0109] FIG. 7A shows an example of an averaged optical spectrum 701 at the wafer 170. The averaged optical spectrum 701 includes a first primary wavelength 702_1 and a second primary wavelength 702_2. In the example of FIG. 7A, the first primary wavelength 702_1 and the second primary wavelength 702_2 are separated by a spectral peak separation 703. The spectral peak separation 703 is such that the first primary wavelength 702_1 and the second primary wavelength 702_2 are distinct, and the average optical spectrum 701 includes a spectral region of little to no intensity between the wavelengths 702_1 and 702_2.

[0110] To accomplish MFI an element in an optical train conveying the laser light to where it is used is moved back-and-forth (dithered) between two angular positions with the light having the first wavelength when the element is in one of the positions and having the second wavelength when the element is in the other of the positions. The element is moved under the control of a command voltage applied to an EAE, e.g., a PZT, a stepper motor, a valve, a pressure-controlled device, an electromagnet, a solenoid, another type of piezoelectric device, a linear motor, a hydraulic actuator, a voice coil, and/or any other type of device capable of generating a motive force under the command of a control signal.

[0111] FIG. 7B is a plot of pulse-to-pulse wavelength measurement against pulse index number for part of a burst of pulses. The top dotted line indicates a measured wavelength λ_{ODD} of the odd-numbered pulses as a positive offset from a central wavelength λ_0. The bottom dotted line indicates a measured wavelength λ_{EVEN} of the even-numbered pulses as a negative offset from the central wavelength λ_0. In other words, the wavelength alternates between λ_{ODD} and λ_{EVEN} with each successive pulse, i.e., pulse-by-pulse. Other patterns may be used instead depending on the desired dosing at the two depths. The central wavelength will in general be the central wavelength of the pulses of laser radiation before they are shifted up or down, that is, red shifted or blue shifted.

[0112] As mentioned above, in an arrangement such as that described during single color operation one or more of the optical elements in the LNM are used for coarse wavelength adjustments and others of the optical elements in the LNM are used for fine wavelength adjustments. To provide for multi-color (e.g., two color) operation in such arrangements, at least some of the optical elements in the LNM used for fine wavelength adjustments during single color operation are used instead to generate two wavelengths.

[0113] Also as mentioned, such arrangements are subject to several limitations. During two color operation the oscillating prism requires a larger angle dither to achieve larger peak separation. Designing an actuator which would create a larger angle dither is challenging. Such an actuator would require a much higher electrical capacitance on the actuator and much higher drive power (higher currents) control electronics. Also, the removal of the fine wavelength control to achieve dual wavelength capability has a negative effect on wavelength stability. In addition the design described above has limited efficiency.

[0114] In accordance with an aspect of an embodiment these limitations are averted by introducing a mirror into the radiation path in the LNM which is positioned to generate multiple wavelengths. Such an arrangement is shown in FIG. 8 for an LNM 800. The arrangement includes optical elements, e.g., prisms 820, 830, 840, and 850 as shown. The arrangement also includes a mirror 860. The mirror 860 may be a plane mirror as shown in the example of FIG. 8. In other arrangements the mirror 860 may be a curved mirror such as a concave or convex mirror. In the arrangement shown a light beam 810 enters a first prism 820. Light from the prism 820 propagates to a prism 840 which is used for wavelength fine control for both single color and two color operation. The light from the prism 840 is caused to impinge upon and be reflected by a mirror 860. The mirror 860 is dithered between two angular positions as indicated by the curved arrow. The mirror 860 is arranged such that it causes the LNM 800 to generate light having a first wavelength when the mirror 860 is in one of the angular positions and to generate light having a second wavelength when the mirror 860 is in the other of the two angular positions. In the arrangement shown a relatively small dither angle can produce a relatively large peak separation. For example, a 1.5 mRad angle dither can produce a 45 pm separation. A prism 850 may be used for coarse wavelength adjustments and control. Ultimately the light originally introduced as beam 810 is incident on the grating 870 with the angle of incidence determining at least one of the spectral features, e.g., wavelength, of the radiation leaving the LNM 800 as explained above.

[0115] Each of the optical elements, prisms 820, 830, 840, and 850 and mirror 860 in the depicted arrangement is coupled to EAE 825, 835, 845, 855, and 865, respectively, each arranged to rotate its respective optical element under the control of an applied control signal in an arrangement such as that shown in and described in connection with FIG. 2B. More specifically, the EAES 825, 835, 845, 855, and 865 are controlled by a controller 880 which may or may not be part of the control system 250 or another control system. The controller 880 receives a control signal 885 which may be generated on the basis, for example, of a measured center wavelength of the light beam 810, a measured peak separation of the wavelengths of alternating pulses of the light beam 810, or another measurement.

[0116] Also as indicated by the broken boxes in FIG. 8, the prism 840 and its associated EAE 845 may be regarded as a fine wavelength control assembly 847 for both single color and two color operation. Similarly, the prism 850 and its associated EAE 855 may be regarded as a coarse wavelength control assembly 857 and the mirror 860 and its associated EAE 865 as a wavelength switching assembly 867 which switches the output wavelength of the LNM 800 between two separated set points. It will be appreciated by one of ordinary skill in the art that for some arrangements and implementations the order of the positions of the fine wavelength control assembly and the coarse wavelength control assembly in the optical path may be reversed.

[0117] The arrangement shown FIG. 8 makes it possible to increase the deviation angle between the mirror 860 and the prism 855 with a smaller amount of dither angle. This offers the possibility of an increased dither range without requiring additional power. This also reduces what is required of, and so reduces the strain and design constraints on, the EAE 865 coupled to the mirror 860. The design also offers the possibility of achieving the same degree of fine wavelength control in a multifocus mode as in the single focus mode because the same components are used for fine wavelength control in both modes. This is as opposed to a conventional arrangement in which the components used for fine wavelength control in a single focus mode are tasked with generating multiple wavelengths in the multifocus mode instead of performing fine wavelength control. Also, the embodiment of FIG. 8 allows higher laser energy per pulse because the design permits optimization of the orientations of the prisms to reduce the magnification of the beam 810 by the LNM 800.

[0118] Thus, the prism 840 is used for wavelength fine control using EAE actuator 845. A second EAE actuator 865 is coupled to the mirror 860 to generate two wavelengths by dithering (oscillating) the mirror 860. The positions of the mirror 860 and the prism 840 can be controlled to obtain the desired wavelengths and peak separation stability. At the same time, the magnification from the LNM 800 can be reduced and the LNM aperture width can be increased to increase laser efficiency and increase laser power output.

[0119] FIG. 9 is a flow chart for carrying out a method of MFI according to an aspect of an embodiment. A pulse of laser radiation is received in a step S10. In a step S20 a prism is used to refract laser radiation for fine wavelength control. In other words, the prism is used to slightly change an angle of incidence of the radiation on a diffraction grating to affect a fine control of the wavelength of the radiation. Then , in a step S30, a mirror is used to deflect the laser radiation by a first amount. Then, in a step S40, a prism is used to refract the laser radiation for coarse wavelength control. Then, in a step S50, the laser radiation is caused to shine on a grating to obtain laser radiation having a first adjusted wavelength, in other words laser radiation that has been coarsely and finely adjusted to the first color to be used for MFI.

[0120] In the next step of the method, that is, step S60, another pulse of radiation is received. In step S70 a prism is used to refract laser radiation for fine wavelength control. Then, in a step S80, the mirror is used to deflect the laser radiation by a second amount. This is achieved, for example, by rotating the mirror between a first angular position and a second angular position between pulses. Then, in a step S90, a prism is used to refract the laser radiation for coarse wavelength control. Then, in a step S100, the laser radiation is caused to shine on the grating to obtain laser radiation having a second adjusted wavelength, that is, wavelength of the second color, the wavelength of which has been both coarsely and finely adjusted by the prisms. The process then reverts to step S10 to receive another pulse of laser radiation. At some point before repeating step S30 the mirror is returned to its first angular position.

[0121] As shown in FIG. 10, various embodiments and components therein can be implemented, for example, using one or more well-known computer systems, such as, for example, the example embodiments, systems, and/or devices shown in the figures or otherwise described. Computer system 1200 can be any well-known computer capable of performing the functions described herein.

[0122] Computer system 1200 includes one or more processors (also called central processing units, or CPUs), such as a processor 1210. Processor 1210 is connected to a communication infrastructure or bus 1220.

[0123] One or more processors 1210 may each be a graphics processing unit (GPU). In an embodiment, a GPU is a processor that is a specialized electronic circuit designed to process mathematically intensive applications. The GPU may have a parallel structure that is efficient for parallel processing of large blocks of data, such as mathematically intensive data common to computer graphics applications, images, videos, etc.

[0124] Computer system 1200 also includes user input/output device(s) 1230, such as monitors, keyboards, pointing devices, etc., that communicate with communication infrastructure 1220 through user input/output interface(s) 1240.

[0125] Computer system 1200 also includes a main or primary memory 1250, such as random access memory (RAM). Main memory 1250 may include one or more levels of cache. Main memory 1250 has stored therein control logic (i.e., computer software) and/or data.

[0126] Computer system 1200 may also include one or more secondary storage devices or memory 1260. Secondary memory 1260 may include, for example, a hard disk drive 1280 and/or a removable storage device or drive 1290. Removable storage drive 1290 may be a floppy disk drive, a magnetic tape drive, a compact disk drive, an optical storage device, tape backup device, and/or any other storage device/drive.

[0127] Hard disk drive 1280 may interact with a removable storage unit 1300. Removable storage unit 1300 includes a computer usable or readable storage device having stored thereon computer software (control logic) and/or data. Removable storage unit 1300 may be a floppy disk, magnetic tape, compact disk, DVD, optical storage disk, and/ any other computer data storage device. Other examples of the removable storage unit 1300 may include a program cartridge and cartridge interface (such as that found in video game devices), a removable memory chip (such as an EPROM or PROM) and associated socket, a memory stick and USB port, a memory card and associated memory card slot, and/or any other removable storage unit and associated interface. Hard disk drive 1280 reads from and/or writes to removable storage unit 1300 in a well-known manner.

[0128] Similarly, removable storage device or drive 1290 may interact with a removable storage unit 1310. Removable storage unit 1310 includes a computer usable or readable storage device having stored thereon computer software (control logic) and/or data. Removable storage unit 1310 may be a floppy disk, magnetic tape, compact disk, DVD, optical storage disk, and/ any other computer data storage device. Other examples of the removable storage unit 1310 may include a program cartridge and cartridge interface (such as that found in video game devices), a removable memory chip (such as an EPROM or PROM) and associated socket, a memory stick and USB port, a memory card and associated memory card slot, and/or any other removable storage unit and associated interface. Removable storage device or drive 1290 reads from and/or writes to removable storage unit 1310 in a well-known manner.

[0129] Computer system 1200 may further include a communication or network interface 1320. Communication interface 1320 enables computer system 1200 to communicate and interact with any combination of remote devices, remote networks, remote entities, etc. (individually and collectively referenced by reference number 1330). For example, communication interface 1320 may allow computer system 1200 to communicate with remote devices 1330 over communications path 1340, which may be wired and/or wireless, and which may include any combination of LANs, WANs, the Internet, etc. Control logic and/or data may be transmitted to and from computer system 1200 via communications path 1340.

[0130] In an embodiment, a non-transitory, tangible apparatus or article of manufacture comprising a non-transitory, tangible computer useable or readable medium having control logic (software) stored thereon is also referred to herein as a computer program product or program storage device. This includes, but is not limited to, computer system 1200, main memory 1250, secondary memory 1260, and removable storage units 1300 and 1310, as well as tangible articles of manufacture embodying any combination of the foregoing. Such control logic, when executed by one or more data processing devices (such as computer system 1200), causes such data processing devices to operate as described herein.

[0131] Based on the teachings contained in this disclosure, it will be apparent to persons skilled in the relevant art(s) how to make and use embodiments of this disclosure using data processing devices, computer systems and/or computer architectures other than that shown in FIG. 10. In particular, embodiments may operate with software, hardware, and/or operating system implementations other than those described herein.

[0132] Although specific reference may have been made above to the use of embodiments in the context of optical lithography, it will be appreciated that embodiments may be used in other applications, for example imprint lithography, and where the context allows, is not limited to optical lithography.

[0133] 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.

[0134] It is to be appreciated 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 may set forth one or more but not all exemplary embodiments as contemplated by the inventor(s), and thus, are not intended to limit the embodiments and the appended claims in any way.

[0135] The embodiments have 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.

[0136] The foregoing description of the specific embodiments will so fully reveal the general nature of the embodiments that others can, based on this disclosure and applying knowledge within the skill of the art, readily modify and/or adapt for various applications such specific embodiments, without undue experimentation, without departing from the general concept of the embodiments. Therefore, such adaptations and modifications are intended to be within the meaning and range of equivalents of the disclosed embodiments, based on the teaching and guidance presented herein.

[0137] Additionally, all or a portion of any aspect and/or embodiment may be utilized with all or a portion of any other aspect and/or embodiment, unless stated otherwise. Features, materials, characteristics, or groups described in conjunction with a particular aspect, embodiment, or example are to be understood to be applicable to any other aspect, embodiment or example described in this section or elsewhere in this specification unless incompatible therewith. All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

[0138] Furthermore, certain features that are described in this disclosure in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations, one or more features from a claimed combination can, in some cases, be excised from the combination, and the combination may be claimed as a subcombination or variation of a subcombination.

[0139] Moreover, while operations may be depicted in the drawings or described in the specification in a particular order, such operations need not be performed in the particular order shown or in sequential order, or that all operations be performed, to achieve desirable results. Other operations that are not depicted or described can be incorporated in the example methods and processes. For example, one or more additional operations can be performed before, after, simultaneously, or between any of the described operations. Further, the operations may be rearranged or reordered in other implementations. Those skilled in the art will appreciate that in some embodiments, the actual steps taken in the processes illustrated and/or disclosed may differ from those shown in the figures. Depending on the embodiment, certain of the steps described above may be removed, others may be added.

[0140] Furthermore, the features and attributes of the specific embodiments disclosed above may be combined in different ways to form additional embodiments, all of which fall within the scope of the present disclosure. Also, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described components and systems can generally be integrated together in a single product or packaged into multiple products.

[0141] For purposes of this disclosure, certain aspects, advantages, and novel features are described herein. Not necessarily all such advantages may be achieved in accordance with any particular embodiment. Thus, for example, those skilled in the art will recognize that the disclosure may be embodied or carried out in a manner that achieves one advantage or a group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

[0142] Conditional language, such as “can,” “could,” “might,” or “may,” unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements, and/or steps. Thus, such conditional language is not generally intended to imply that features, elements, and/or steps are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without user input or prompting, whether these features, elements, and/or steps are included or are to be performed in any particular embodiment.

[0143] Conjunctive language such as the phrase "at least one of X, Y, and Z," unless specifically stated otherwise, is otherwise understood with the context as used in general to convey that an item, term, etc. may be either X, Y, or Z. Thus, such conjunctive language is not generally intended to imply that certain embodiments require the presence of at least one of X, at least one of Y, and at least one of Z.

[0144] The implementations can be further described using the following clauses:

1. Apparatus comprising:

a first wavelength control assembly arranged to receive and refract laser radiation;

a wavelength switching assembly arranged to receive the laser radiation refracted by the first wavelength control assembly, the wavelength switching assembly having a first state in which the wavelength switching assembly deflects the laser radiation by a first amount and a second state in which the wavelength switching assembly deflects the laser radiation by a second amount different from the first amount; and

a second wavelength control assembly arranged to receive and refract laser radiation deflected by the wavelength switching assembly,

the laser radiation refracted by the second wavelength control assembly being directed towards a diffraction grating with a wavelength of the laser radiation diffracted by the diffraction grating being dependent on an angle of incidence of the laser radiation on the diffraction grating.

2. The apparatus of clause 1 wherein the first wavelength control assembly is a fine wavelength control assembly and the second wavelength control assembly is a coarse wavelength control assembly.

3. The apparatus of clause 1 wherein the first wavelength control assembly is a coarse wavelength control assembly and the second wavelength control assembly comprises a fine wavelength control assembly.

4. The apparatus of clause 1 wherein the first wavelength control assembly comprises at least one prism.

5. The apparatus of clause 1 wherein the second wavelength control assembly comprises at least one prism.

6. The apparatus of clause 1 wherein the wavelength switching assembly comprises a mirror.

7. The apparatus of clause 6 wherein the mirror comprises a plane mirror.

8. The apparatus of clause 6 wherein the first state of the wavelength switching assembly corresponds to a first angular position of the mirror and the second state of the wavelength switching assembly corresponds to a second angular position of the mirror different from the first angular position.

9. The apparatus of clause 8 further comprising an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal.

10. The apparatus of clause 9 further comprising a controller adapted to generate the control signal.

11. The apparatus of clause 1 wherein the laser radiation is fired in one or more bursts, each burst being made up of a plurality of pulses, and wherein in the first state the wavelength switching assembly causes a primary wavelength of some of the pulses to assume a first value and in the second state causes others of the pulses to assume a second value different from the first value by a target primary wavelength separation amount.

12. The apparatus of clause 11 wherein the wavelength switching assembly comprises a mirror and wherein the first state of the wavelength switching assembly corresponds to a first angular position of the mirror and the second state of the wavelength switching assembly corresponds to a second angular position of the mirror different from the first angular position.

13. The apparatus of clause 12 wherein the wavelength switching assembly further comprises an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal.

14. The apparatus of clause 13 further comprising a controller adapted to generate the control signal.

15. The apparatus of clause 14 wherein the controller is configured to cause the wavelength switching assembly to cause the primary wavelength of the pulses to alternate between the first value and the second value on a pulse-by-pulse basis.

16. A method comprising:

performing a first wavelength control operation on a pulse of laser radiation by refracting the pulse of laser radiation using at least one first wavelength control prism to produce a refracted pulse of laser radiation;

deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation;

performing a second wavelength control operation on the deflected pulse of laser radiation by refracting the deflected pulse of laser radiation using at least one prism to produce an additionally refracted pulse of laser radiation; and

diffracting the additionally refracted pulse of laser radiation using a diffraction grating to produce a diffracted pulse of laser radiation, with a wavelength of the diffracted pulse of laser radiation being dependent on an angle of incidence of the additionally refracted laser radiation on the diffraction grating.

17. The method of clause 16 wherein the first wavelength control operation is a fine wavelength control operation and the second wavelength control operation is a coarse wavelength control operation.

18. The method of clause 16 wherein the first wavelength control operation is a coarse wavelength control operation and the second wavelength control operation is a fine wavelength control operation.

19. The method of clause 16 wherein deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation comprises causing the refracted pulse of laser radiation to

impinge upon a mirror and controlling the mirror to be in one of a first angular position or a second angular position of the mirror different from the first angular position.

20. The method of clause 19 wherein controlling the mirror to be in one of a first angular position or a second angular position of the mirror different from the first angular position further comprises controlling an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal.

21. The method of clause 20 further comprising generating the control signal.

22. A method of generating laser output at a first wavelength or at a second wavelength, the method comprising:

generating laser radiation at a wavelength having a base wavelength value; and

controlling a mirror actuator to adjust a mirror angle of a mirror to shift a value of the wavelength of the laser radiation to dither between a first wavelength value and a second wavelength value.

23. The method as in clause 22, further comprising controlling a prism actuator to adjust a prism angle of a first prism to adjust the wavelength of the laser radiation.

24. The method as in clause 23, wherein the mirror is located along an optical path between the first prism and a second prism, the method further comprising controlling a second prism actuator to adjust a second prism angle of the second prism to adjust the wavelength of the laser radiation more coarsely than the adjustment by the first prism.

25. An apparatus comprising:

a diffraction grating in an optical path of a beam of laser radiation;

a first prism in the optical path of the beam of laser radiation and moveable to adjust an angle of incidence of the beam of laser radiation on the diffraction grating;

a second prism in the optical path of the beam of laser radiation and moveable to adjust an angle of incidence of the beam of laser radiation on the diffraction grating; and

a mirror interposed in the optical path of the beam of laser radiation between the first prism and the second prism and rotatable between a first position which selects a first angle of incidence of the beam of laser radiation on the diffraction grating and a second position which selects a second angle of incidence of the beam of laser radiation on the diffraction grating.

26. The apparatus of clause 25 wherein the a first prism is moveable to finely adjust the angle of incidence of the beam of laser radiation on the diffraction grating and the second prism is moveable to coarsely adjust an angle of incidence of the beam of laser radiation on the diffraction grating.

27. The apparatus of clause 25 wherein the a first prism is moveable to coarsely adjust the angle of incidence of the beam of laser radiation on the diffraction grating and the second prism is moveable to finely adjust an angle of incidence of the beam of laser radiation on the diffraction grating.

28. The apparatus of clause 25 further comprising a controller configured to move the first and second prisms based on feedback from a center wavelength detector that detects a center wavelength of the laser radiation.

29. The apparatus of clause 28, wherein the controller is configured to move the first and second prisms on a pulse-to-pulse basis.

30. The apparatus of clause 25, wherein the first and second prisms are beam expanding prisms.

31. A method comprising:

oscillating a rotational position of a mirror to change an angle of incidence of pulses of laser radiation on a grating on a pulse-by-pulse basis and so to change a wavelength of the laser radiation between two set points pulse-by-pulse;

controlling a first prism to perform a first adjustment of the angle of incidence of the laser radiation on the grating; and

controlling a second prism to perform a second adjustment of the angle of incidence of the laser radiation on the grating.

32. The method of clause 31 wherein the first adjustment is a fine adjustment and the second adjustment is a coarse adjustment.

33. The method of clause 31 wherein the first adjustment is a coarse adjustment and the second adjustment is a fine adjustment.

34. A non-transitory computer-readable medium storing instructions that, when executed by a processor, cause the processor to perform operations, the operations comprising:

performing a first wavelength control on a pulse of laser radiation by refracting the pulse of laser radiation using at least one first wavelength control prism to produce a refracted pulse of laser radiation;

deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation;

performing a second wavelength control on the deflected pulse of laser radiation by refracting the deflected pulse of laser radiation using at least one second prism to produce an additionally refracted pulse of laser radiation; and

diffracting the additionally refracted pulse of laser radiation using a diffraction grating to produce a diffracted pulse of laser radiation, with a wavelength of the diffracted pulse of laser radiation being dependent on an angle of incidence of the additionally refracted laser radiation on the diffraction grating.

[0145] The above-described implementations and other implementations are within the scope of the following claims.

CLAIMS

1. Apparatus comprising:

a first wavelength control assembly arranged to receive and refract laser radiation;

a wavelength switching assembly arranged to receive the laser radiation refracted by the first wavelength control assembly, the wavelength switching assembly having a first state in which the wavelength switching assembly deflects the laser radiation by a first amount and a second state in which the wavelength switching assembly deflects the laser radiation by a second amount different from the first amount; and

a second wavelength control assembly arranged to receive and refract laser radiation deflected by the wavelength switching assembly,

the laser radiation refracted by the second wavelength control assembly being directed towards a diffraction grating with a wavelength of the laser radiation diffracted by the diffraction grating being dependent on an angle of incidence of the laser radiation on the diffraction grating.

2. The apparatus of claim 1 wherein the first wavelength control assembly is a fine wavelength control assembly and the second wavelength control assembly is a coarse wavelength control assembly.

3. The apparatus of claim 1 wherein the first wavelength control assembly is a coarse wavelength control assembly and the second wavelength control assembly comprises a fine wavelength control assembly.

4. The apparatus of claim 1 wherein the first wavelength control assembly comprises at least one prism.

5. The apparatus of claim 1 wherein the second wavelength control assembly comprises at least one prism.

6. The apparatus of claim 1 wherein the wavelength switching assembly comprises a mirror.

7. The apparatus of claim 6 wherein the mirror comprises a plane mirror.

8. The apparatus of claim 6 wherein the first state of the wavelength switching assembly corresponds to a first angular position of the mirror and the second state of the wavelength switching assembly corresponds to a second angular position of the mirror different from the first angular position.

9. The apparatus of claim 8 further comprising an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal.

10. The apparatus of claim 9 further comprising a controller adapted to generate the control signal.

11. The apparatus of claim 1 wherein the laser radiation is fired in one or more bursts, each burst being made up of a plurality of pulses, and wherein in the first state the wavelength switching assembly causes a primary wavelength of some of the pulses to assume a first value and in the second state causes others of the pulses to assume a second value different from the first value by a target primary wavelength separation amount.

12. The apparatus of claim 11 wherein the wavelength switching assembly comprises a mirror and wherein the first state of the wavelength switching assembly corresponds to a first angular position of the mirror and the second state of the wavelength switching assembly corresponds to a second angular position of the mirror different from the first angular position.

13. The apparatus of claim 12 wherein the wavelength switching assembly further comprises an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal.

14. The apparatus of claim 13 further comprising a controller adapted to generate the control signal.

15. The apparatus of claim 14 wherein the controller is configured to cause the wavelength switching assembly to cause the primary wavelength of the pulses to alternate between the first value and the second value on a pulse-by-pulse basis.

16. A method comprising:
performing a first wavelength control operation on a pulse of laser radiation by refracting the pulse of laser radiation using at least one first wavelength control prism to produce a refracted pulse of laser radiation;
deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation;
performing a second wavelength control operation on the deflected pulse of laser radiation by

refracting the deflected pulse of laser radiation using at least one prism to produce an additionally refracted pulse of laser radiation; and

diffracting the additionally refracted pulse of laser radiation using a diffraction grating to produce a diffracted pulse of laser radiation, with a wavelength of the diffracted pulse of laser radiation being dependent on an angle of incidence of the additionally refracted laser radiation on the diffraction grating.

17. The method of claim 16 wherein the first wavelength control operation is a fine wavelength control operation and the second wavelength control operation is a coarse wavelength control operation.

18. The method of claim 16 wherein the first wavelength control operation is a coarse wavelength control operation and the second wavelength control operation is a fine wavelength control operation.

19. The method of claim 16 wherein deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation comprises causing the refracted pulse of laser radiation to impinge upon a mirror and controlling the mirror to be in one of a first angular position or a second angular position of the mirror different from the first angular position.

20. The method of claim 19 wherein controlling the mirror to be in one of a first angular position or a second angular position of the mirror different from the first angular position further comprises controlling an actuator mechanically coupled to the mirror and configured to rotate the mirror between the first angular position and the second angular position in response to a control signal.

21. The method of claim 20 further comprising generating the control signal.

22. A method of generating laser output at a first wavelength or at a second wavelength, the method comprising:

generating laser radiation at a wavelength having a base wavelength value; and

controlling a mirror actuator to adjust a mirror angle of a mirror to shift a value of the wavelength of the laser radiation to dither between a first wavelength value and a second wavelength value.

23. The method as in claim 22, further comprising controlling a prism actuator to adjust a prism angle of a first prism to adjust the wavelength of the laser radiation.

24. The method as in claim 23, wherein the mirror is located along an optical path between the first prism and a second prism, the method further comprising controlling a second prism actuator to

adjust a second prism angle of the second prism to adjust the wavelength of the laser radiation more coarsely than the adjustment by the first prism.

25. An apparatus comprising:
a diffraction grating in an optical path of a beam of laser radiation;
a first prism in the optical path of the beam of laser radiation and moveable to adjust an angle of incidence of the beam of laser radiation on the diffraction grating;
a second prism in the optical path of the beam of laser radiation and moveable to adjust an angle of incidence of the beam of laser radiation on the diffraction grating; and
a mirror interposed in the optical path of the beam of laser radiation between the first prism and the second prism and rotatable between a first position which selects a first angle of incidence of the beam of laser radiation on the diffraction grating and a second position which selects a second angle of incidence of the beam of laser radiation on the diffraction grating.

26. The apparatus of claim 25 wherein the a first prism is moveable to finely adjust the angle of incidence of the beam of laser radiation on the diffraction grating and the second prism is moveable to coarsely adjust an angle of incidence of the beam of laser radiation on the diffraction grating.

27. The apparatus of claim 25 wherein the a first prism is moveable to coarsely adjust the angle of incidence of the beam of laser radiation on the diffraction grating and the second prism is moveable to finely adjust an angle of incidence of the beam of laser radiation on the diffraction grating.

28. The apparatus of claim 25 further comprising a controller configured to move the first and second prisms based on feedback from a center wavelength detector that detects a center wavelength of the laser radiation.

29. The apparatus of claim 28, wherein the controller is configured to move the first and second prisms on a pulse-to-pulse basis.

30. The apparatus of claim 25, wherein the first and second prisms are beam expanding prisms.

31. A method comprising:
oscillating a rotational position of a mirror to change an angle of incidence of pulses of laser radiation on a grating on a pulse-by-pulse basis and so to change a wavelength of the laser radiation between two set points pulse-by-pulse;
controlling a first prism to perform a first adjustment of the angle of incidence of the laser radiation on the grating; and

controlling a second prism to perform a second adjustment of the angle of incidence of the laser radiation on the grating.

32. The method of claim 31 wherein the first adjustment is a fine adjustment and the second adjustment is a coarse adjustment.

33. The method of claim 31 wherein the first adjustment is a coarse adjustment and the second adjustment is a fine adjustment.

34. A non-transitory computer-readable medium storing instructions that, when executed by a processor, cause the processor to perform operations, the operations comprising:
performing a first wavelength control on a pulse of laser radiation by refracting the pulse of laser radiation using at least one first wavelength control prism to produce a refracted pulse of laser radiation;
deflecting the refracted pulse of laser radiation using a mirror to produce a deflected pulse of laser radiation;
performing a second wavelength control on the deflected pulse of laser radiation by refracting the deflected pulse of laser radiation using at least one second prism to produce an additionally refracted pulse of laser radiation; and
diffracting the additionally refracted pulse of laser radiation using a diffraction grating to produce a diffracted pulse of laser radiation, with a wavelength of the diffracted pulse of laser radiation being dependent on an angle of incidence of the additionally refracted laser radiation on the diffraction grating.

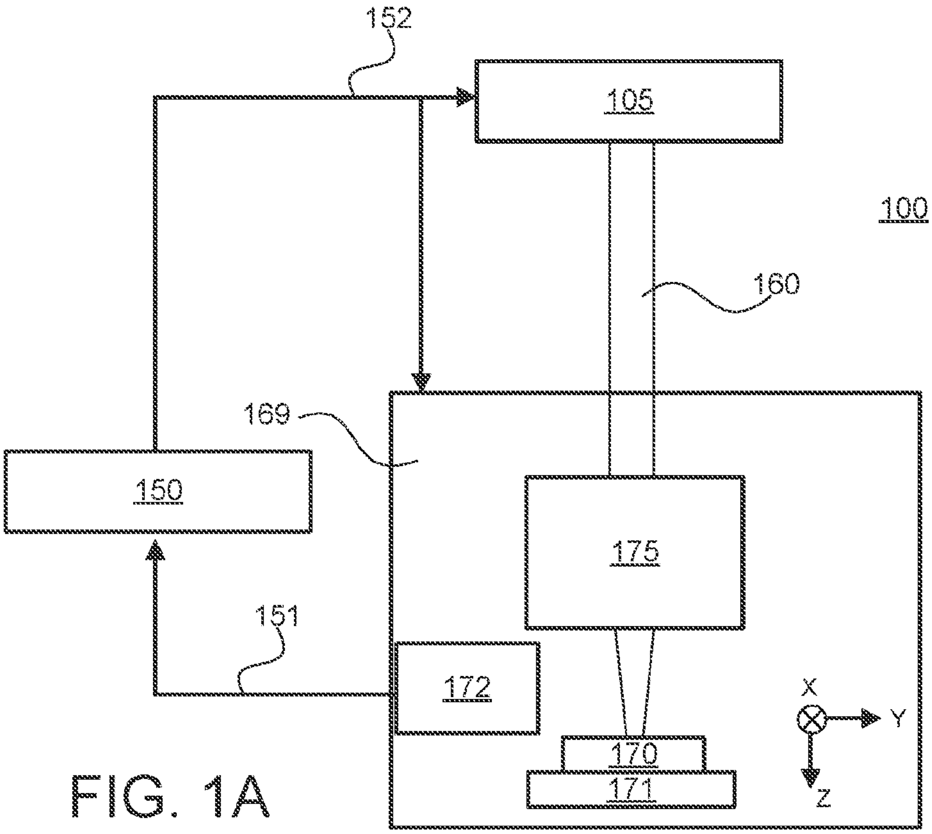


FIG. 1A

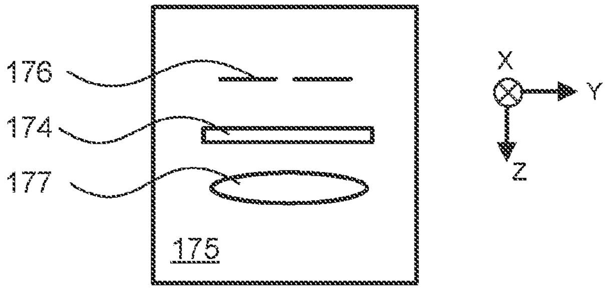


FIG. 1B

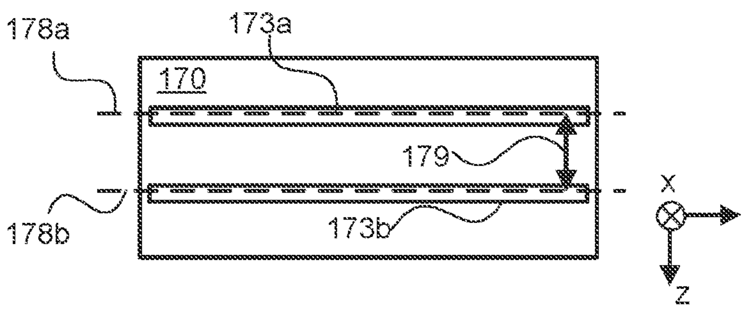
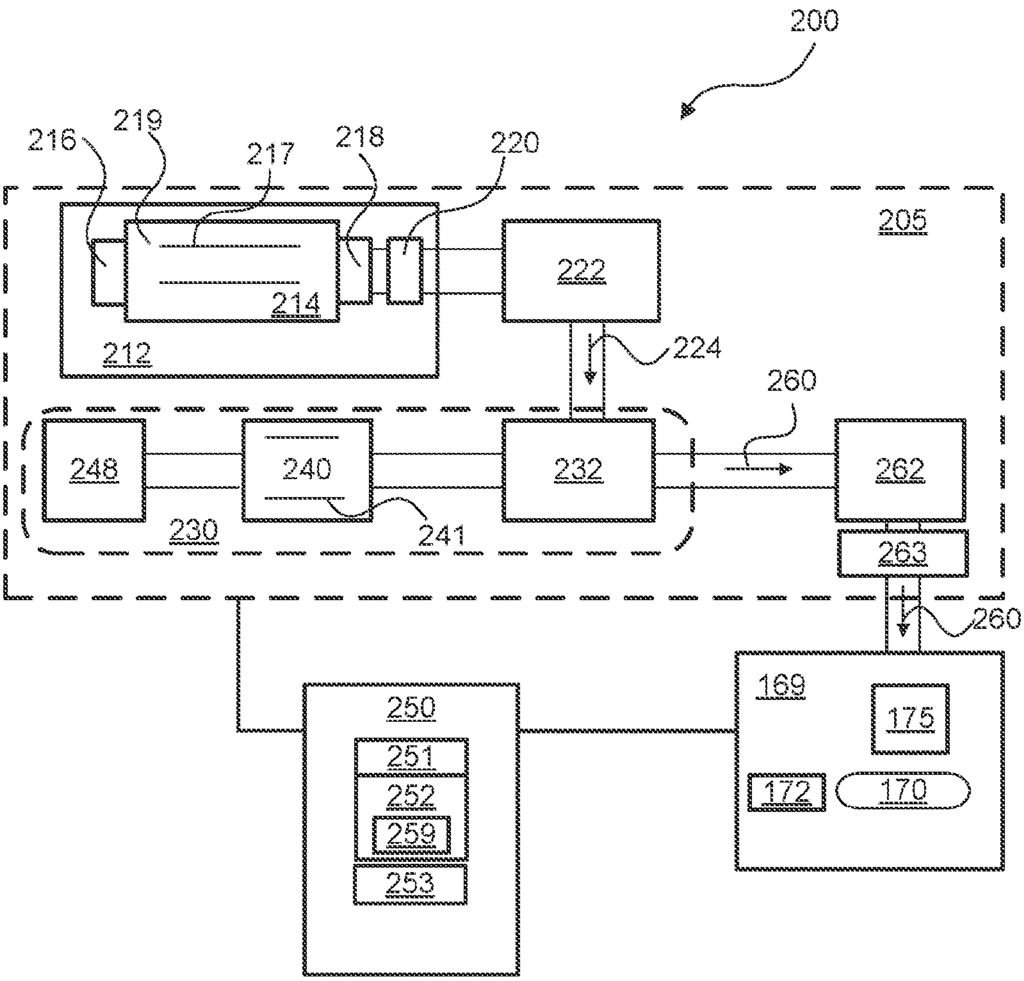


FIG. 1C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214
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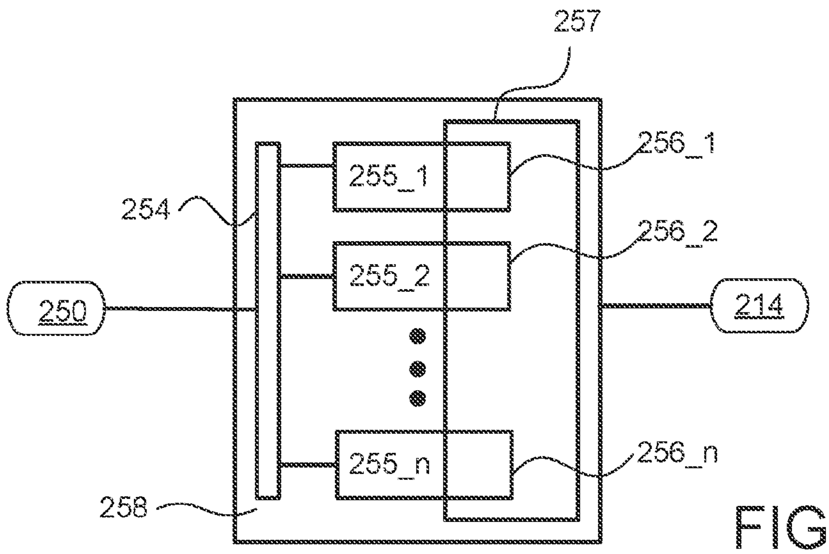
251
252
259
253
172
170

FIG. 2A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214
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256_n
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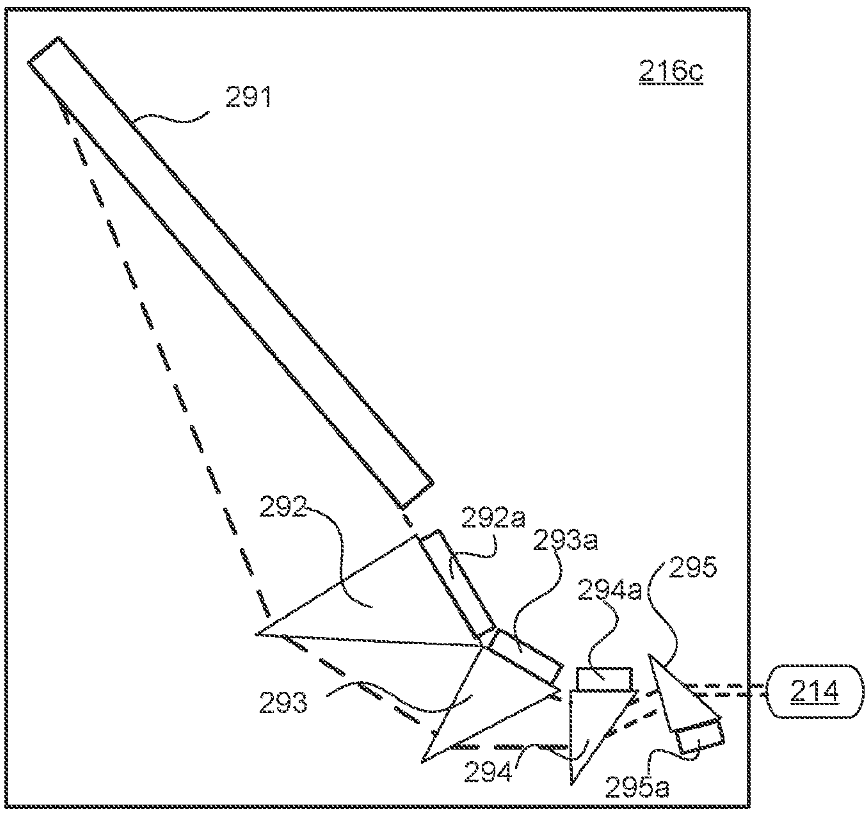
FIG. 2B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293a
294a
295
214
293
294
295a

FIG. 2C

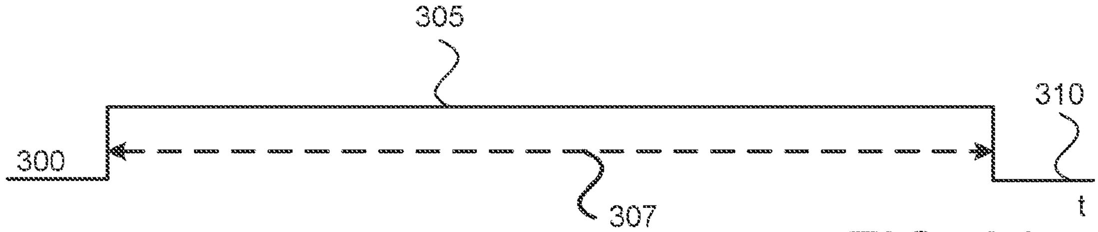


FIG. 3A

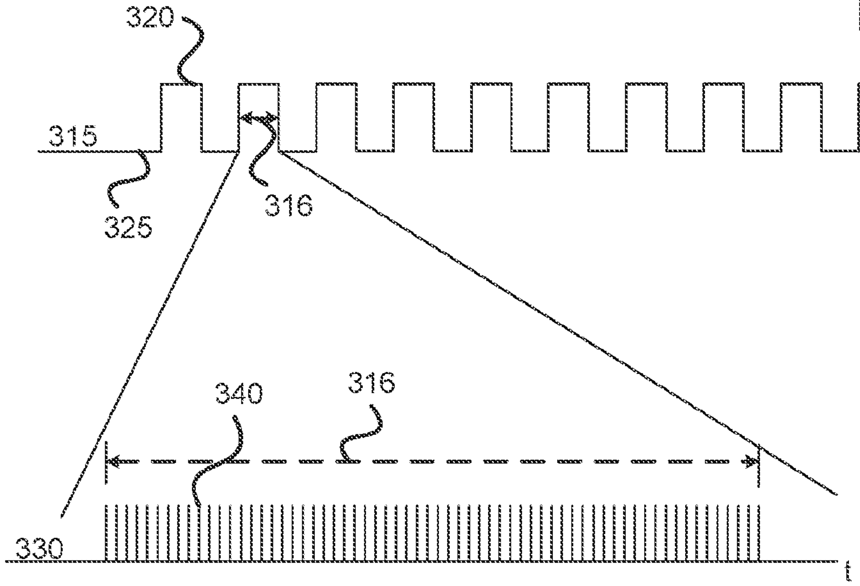
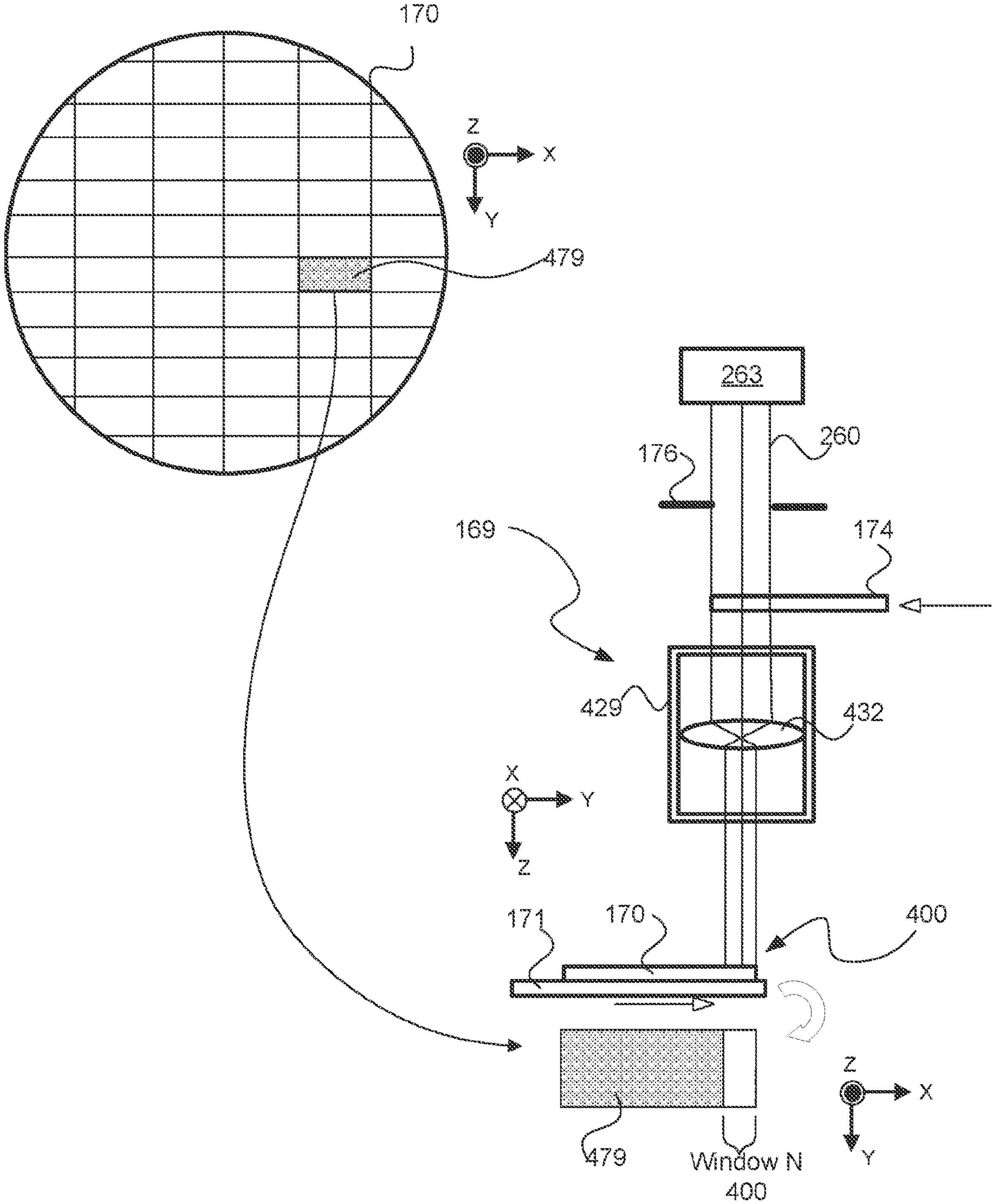


FIG. 3B

FIG. 3C


170
Z
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Y
479
263
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Z
171
170
400
Z
X
Y
479
Window N
400

FIG. 4

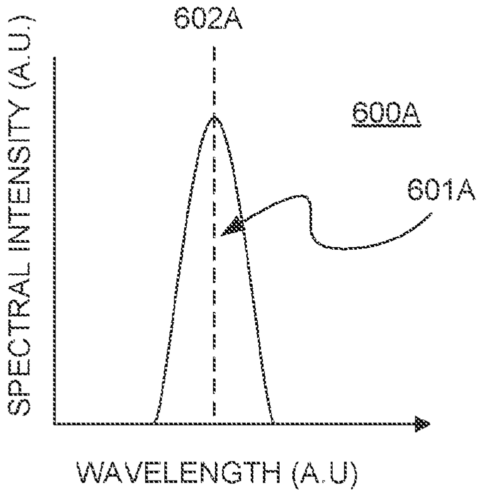
602A
600A
601A
SPECTRAL INTENSITY (A.U.)
WAVELENGTH (A.U)

FIG. 5

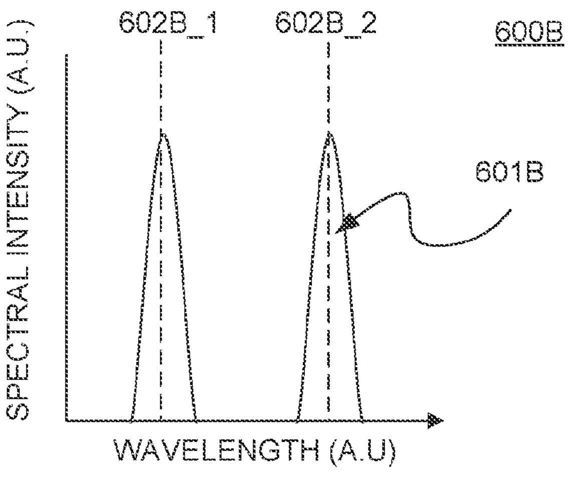
602B_1
602B_2
600B
601B
SPECTRAL INTENSITY (A.U.)
WAVELENGTH (A.U)

FIG. 6

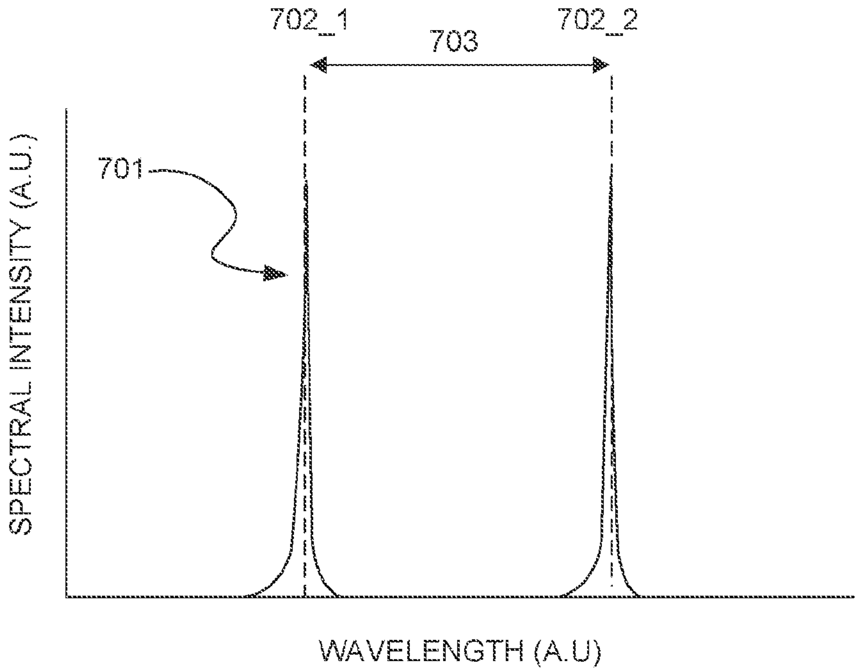
702_1
703
702_2
701
SPECTRAL INTENSITY (A.U.)
WAVELENGTH (A.U)

FIG. 7A

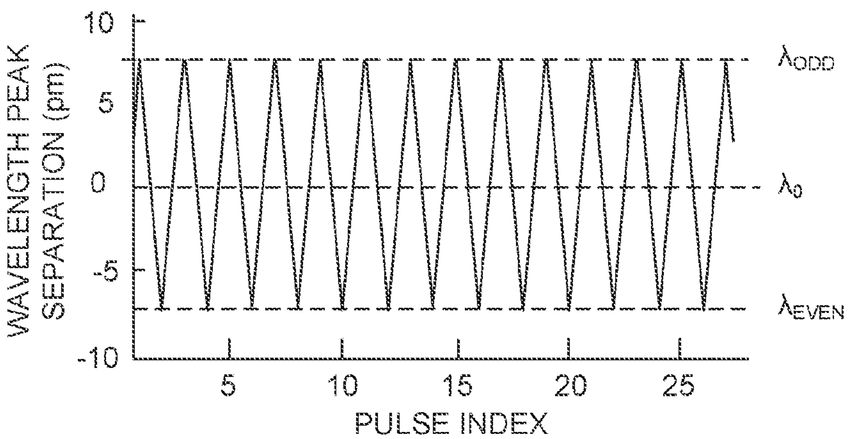
10
5
0
-5
-10
WAVELENGTH PEAK SEPARATION (pm)
λ_{ODD}
λ_0
λ_{EVEN}
5
10
15
20
25
PULSE INDEX

FIG. 7B

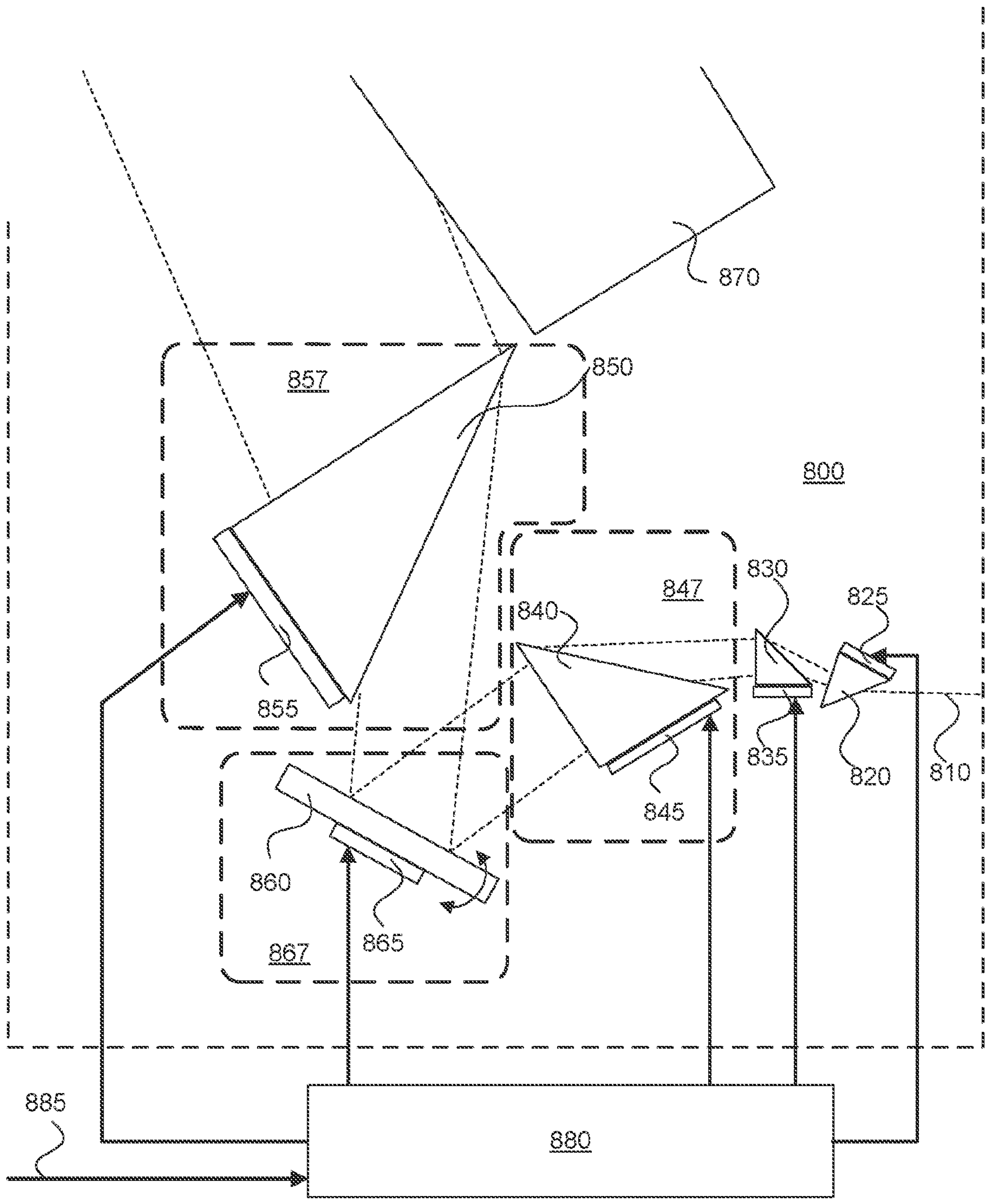
870
857
850
800
847
830
825
840
855
835
820
810
845
860
865
867
885
880

FIG. 8

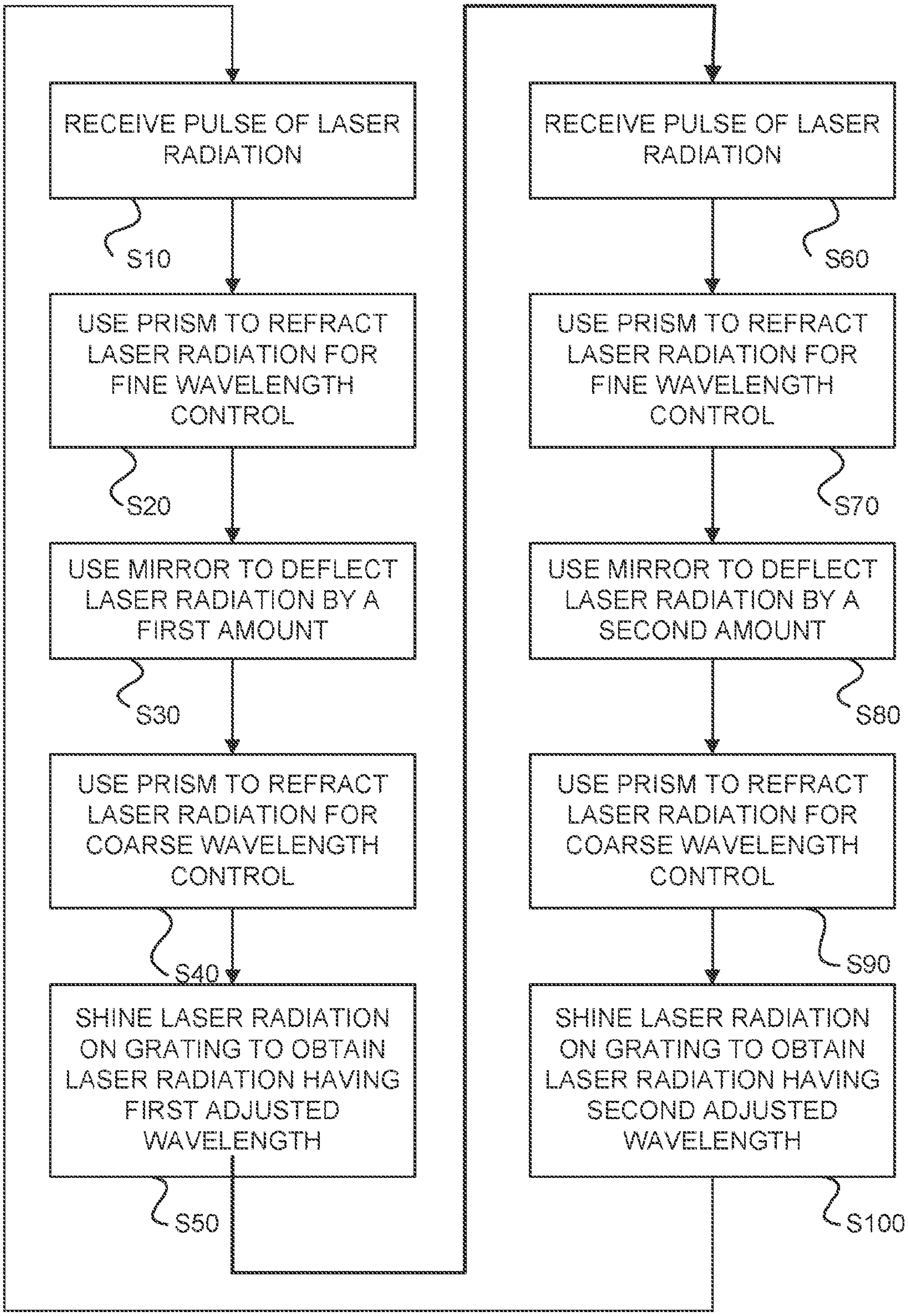
RECEIVE PULSE OF LASER RADIATION
S10
USE PRISM TO REFRACT LASER RADIATION FOR FINE WAVELENGTH CONTROL
S20
USE MIRROR TO DEFLECT LASER RADIATION BY A FIRST AMOUNT
S30
USE PRISM TO REFRACT LASER RADIATION FOR COARSE WAVELENGTH CONTROL
S40
SHINE LASER RADIATION ON GRATING TO OBTAIN LASER RADIATION HAVING FIRST ADJUSTED WAVELENGTH
S50
RECEIVE PULSE OF LASER RADIATION
S60
USE PRISM TO REFRACT LASER RADIATION FOR FINE WAVELENGTH CONTROL
S70
USE MIRROR TO DEFLECT LASER RADIATION BY A SECOND AMOUNT
S80
USE PRISM TO REFRACT LASER RADIATION FOR COARSE WAVELENGTH CONTROL
S90
SHINE LASER RADIATION ON GRATING TO OBTAIN LASER RADIATION HAVING SECOND ADJUSTED WAVELENGTH
S100

FIG. 9

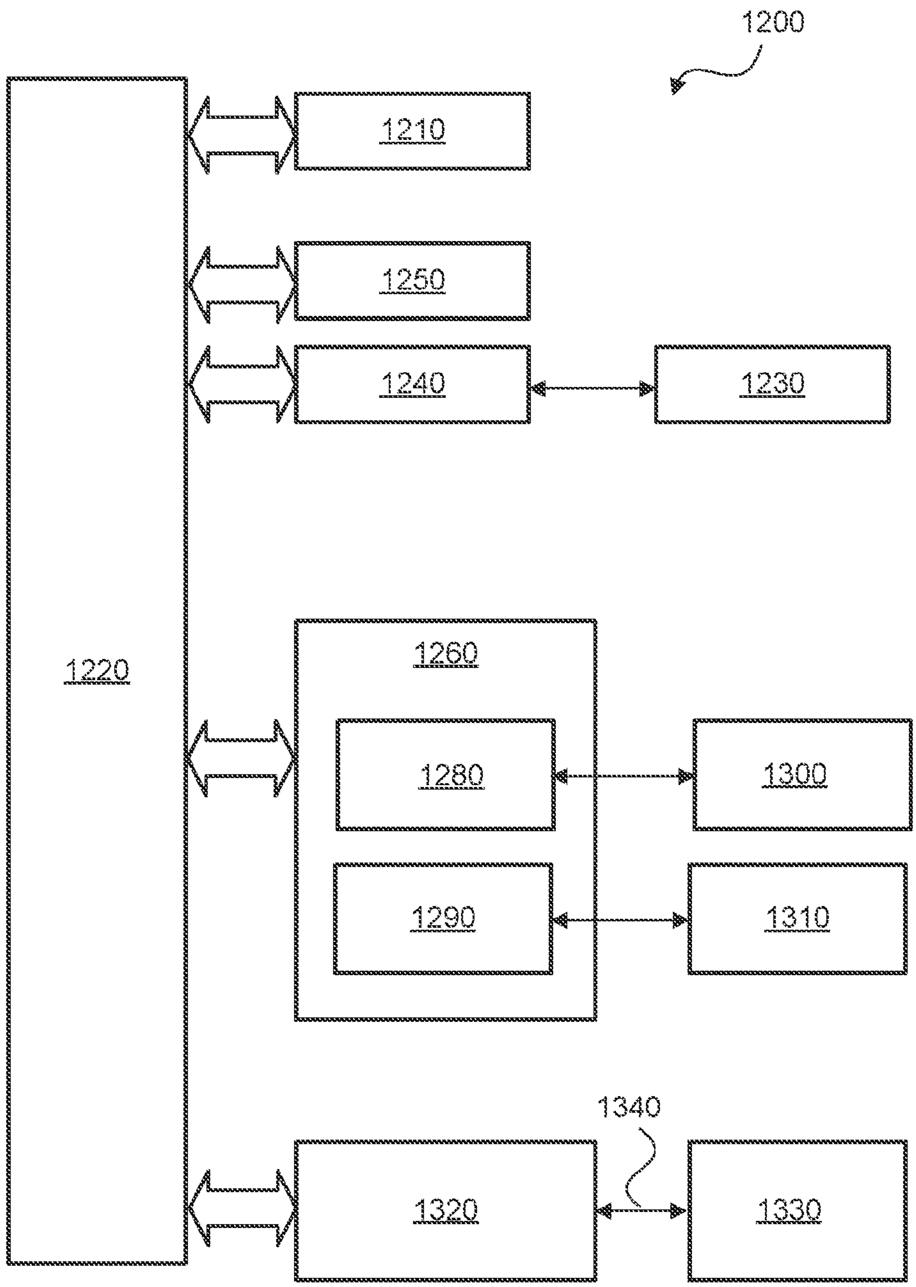
1200
1210
1250
1240
1230
1220
1260
1280
1300
1290
1310
1340
1320
1330

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2024/061569

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01S3/08 H01S3/1055 H01S3/225 G03F7/00 H01S3/139
H01S3/23 H01S3/10
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)
H01S G03F

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2023/096768 A1 (CYMER LLC [US]) 1 June 2023 (2023-06-01) paragraph [0053] - paragraph [0058]; figure 2C paragraph [0091] - paragraph [0093] paragraph [0067] - paragraph [0076]; figures 3A-3C -----	1-5, 11-15, 22,23, 31-33
X	US 2008/151944 A1 (ALGOTS J MARTIN [US] ET AL) 26 June 2008 (2008-06-26) paragraph [0005] - paragraph [0040]; figure 4 ----- -/--	1-34

[X] Further documents are listed in the continuation of Box C.

[X] 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	Date of mailing of the international search report
13 February 2025	26/02/2025

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Hervé, Denis

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2024/061569

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	"APPARATUS FOR AND METHOD OF WAVELENGTH CONTROL FOR MULTIFOCAL IMAGING", RESEARCH DISCLOSURE, KENNETH MASON PUBLICATIONS, HAMPSHIRE, UK, GB , vol. 718, no. 81 17 January 2024 (2024-01-17), XP007152252, ISSN: 0374-4353 Retrieved from the Internet: URL:https://www.researchdisclosure.com/database/RD718081 [retrieved on 2024-01-17] the whole document -----	1-34
A	US 2019/181607 A1 (MIYAMOTO HIROTAKA [JP] ET AL) 13 June 2019 (2019-06-13) paragraph [0039] - paragraph [0061]; figures 4, 5 -----	1-34

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2024/061569

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		WO 2018061210 A1	05-04-2018