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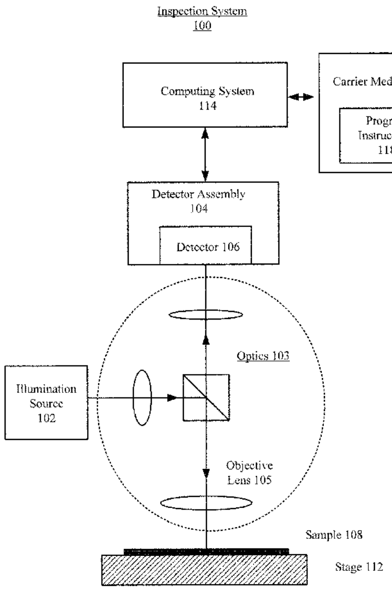

Figure 1

(57) Abstract: A DUV laser includes an optical bandwidth filtering device, such as etalon, which is disposed outside of the laser oscillator cavity of the fundamental laser, and which directs one range of wavelengths into one portion of a frequency conversion chain and another range of wavelengths into another portion of the frequency conversion train, thereby reducing the bandwidth of the DUV laser output while maintaining high conversion efficiency in the frequency conversion chain.

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SYSTEM AND METHOD FOR REDUCING THE BANDWIDTH OF A LASER AND AN INSPECTION SYSTEM AND METHOD USING A LASER

PRIORITY APPLICATION

[0001] The present application claims priority to U.S. Provisional Patent Application 61/955,792, entitled “A System and Method for Reducing the Bandwidth of a Laser and an Inspection System and Method Using a Laser”, filed on March 20, 2014, and incorporated by reference herein.

RELATED APPLICATIONS

[0002] The present application is related to U.S. Provisional Patent Application 61/756,209, entitled “193 nm Laser Using OPO and an Inspection System Using a 193 nm Laser”, filed on January 24, 2013, U.S. Patent Application 14/158,615, entitled “193nm Laser and Inspection System”, filed on January 17, 2014, U.S. Patent Application 13/797,939, entitled “Solid-State Laser and Inspection System Using 193 nm Laser”, filed on March 12, 2013, U.S. Provisional Patent Application 61/764,441, entitled “193 nm Laser and an Inspection System Using a 193 nm Laser”, filed on February 13, 2013, U.S. Patent Application 14/170,384, entitled “193nm Laser and Inspection System”, filed on January 31, 2014, U.S. Provisional Patent Application 61/733,858, entitled “Semiconductor Inspection and Metrology System Using Laser Pulse Multiplier”, filed on December 5, 2012, and U.S. Patent Application 13/711,593, entitled “Semiconductor Inspection and Metrology System Using Laser Pulse Multiplier”, filed on December 11, 2012. These related applications are incorporated by reference herein.

BACKGROUND OF THE DISCLOSURE

Field of the Disclosure

[0003] The present application relates to lasers suitable for generating radiation at deep UV (DUV) and vacuum UV (VUV) wavelengths, and to methods for generating laser light at DUV and VUV wavelengths. In particular, the present application relates to systems and methods for reducing and controlling the spectral bandwidth of DUV and

VUV lasers. The lasers described herein are particularly suitable for use in inspection systems including those used to inspect photomasks, reticles, and semiconductor wafers.

Related Art

[0004] The integrated circuit industry requires inspection tools with increasingly higher sensitivity to detect ever smaller defects and particles whose sizes may be 100 nm or smaller. Furthermore, these inspection tools must operate at high speed to inspect a large fraction or even 100% of the area of a photomask, reticle or wafer in a short period of time, e.g. one hour or less.

[0005] Generally, short wavelengths such as DUV and VUV wavelengths have higher sensitivity for detecting small defects compared with longer wavelengths. Inspection of a photomask or a reticle is preferably done using the same wavelength as the lithography used when printing from the photomask or reticle. Currently, a wavelength of substantially 193.4 nm is used for the most critical lithography steps and a wavelength of substantially 248 nm is used for less critical lithography steps.

[0006] High-speed inspection requires high power lasers to illuminate the samples being inspected with high intensity to detect the small amount of light scattered from small particles or defects or allow detection of small changes in reflectivity due to defects in the pattern. The required laser power levels may range from approximately 100 mW for the inspection of photomasks and reticles up to more than 10 W for the detection of small particles and imperfections on a bare silicon wafer.

[0007] Typically, inspection in the semiconductor industry requires lasers with very narrow bandwidth. Such inspection systems usually use an objective lens with a large field of view (typically from a few hundred microns to a few mm in dimensions) to allow imaging of a large area at high inspection speeds. An objective lens with low distortions and a large field of view is expensive and complex. Requiring that objective lens to operate over a large bandwidth (such as more than a few tens of pm) significantly increases the cost and complexity. DUV lasers with bandwidths of approximately 20 pm or less are very desirable for inspection applications in the semiconductor industry.

[0008] DUV lasers are known in the art. U.S. Patent 5,144,630 entitled “Multiwave Solid State Laser Using Frequency Conversion Techniques” that issued on September 1, 1992 to Lin, and U.S. Patent 5,742,626, entitled “Ultraviolet Solid State Laser Method Of Using Same And Laser Surgery Apparatus”, issued on April 21, 1998 to Mead et al. describe exemplary DUV lasers. In these lasers, fourth and fifth harmonics are generated from a pulsed fundamental infra-red laser operating at a wavelength near 1064 nm, thereby resulting in wavelengths of approximately 266 nm and 213 nm. Lin and Mead also teach generating an infra-red wavelength longer than 1064 nm from the fundamental laser using an optical parametric oscillator (OPO).

[0009] The output bandwidth of a laser oscillator is determined by its intra-cavity dynamics. In prior art pulsed lasers, to further reduce laser bandwidth, various bandwidth limiting devices, such as an etalon, a birefringent filter, or an optical grating, have been incorporated into a laser cavity. Because all of these approaches are invasive, they inevitably introduce detrimental effects to the lasers. These detrimental effects include extra power losses and greater complexity, which often lead to lower laser efficiency, poor thermal stability, tighter misalignment sensitivity, and longer laser system warm-up time. Furthermore, because intra-cavity beam size is often small and predetermined by laser cavity design, and intra-cavity laser power density is normally much higher than laser output power, these intra-cavity components are much more susceptible to damage.

[0010] In prior art pulsed DUV lasers, the bandwidth of the DUV output depends directly on the bandwidth of the fundamental infra-red laser. That is, the broader the bandwidth of the fundamental laser, the broader the DUV output bandwidth. Reducing the bandwidth of a laser requires redesigning the laser oscillator cavity. Because the cavity may control many properties of the laser including bandwidth, repetition rate, as well as average and peak powers, redesigning the cavity to reduce the bandwidth while maintaining the other laser parameters may be a complex and time consuming task.

Furthermore, achieving a specific DUV laser bandwidth specification may not be possible using a readily available infra-red fundamental laser.

[0011] It is well-known that a chirp stretches the length of a laser pulse and reduces its peak power (see, for example, http://www.rp-photonics.com/chirp.html). As non-linear conversion efficiency scales with peak power, a lower peak power would reduce the overall conversion efficiency, thereby limiting the maximum UV power generated from a laser system. Therefore, for a given required bandwidth, close to transform-limited (also called “chirp-free”) pulses are desirable for high non-linear conversion efficiency. However, because of laser intra-cavity dynamics, such as dispersion, spatial-hole burning (SHB), gain saturation, and non-linearity, pulses generated from lasers are often chirped.

[0012] Therefore, a need arises for DUV laser overcoming some, or all, of the above disadvantages. In particular, a need arises for a means of reducing or controlling the bandwidth of a DUV laser.

SUMMARY OF THE DISCLOSURE

[0013] A DUV laser for providing optimized bandwidth control is described. This DUV laser includes a fundamental laser, a frequency conversion module, a frequency mixing module, and an optical bandwidth filtering device. The fundamental laser generates a fundamental wavelength with a fundamental wavelength bandwidth. The optical bandwidth filtering device is positioned to receive the fundamental wavelength, and selects first and second portions from the fundamental wavelength such that the second portion comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion. The frequency conversion module converts the first portion of the fundamental wavelength to provide “signal light” having a second wavelength, and the frequency mixing module mixes the second wavelength with the second portion of the fundamental wavelength to generate a sum (output) wavelength. By utilizing the optical bandwidth filtering device to select the narrower second portion, the present invention reduces system costs by facilitating the use of fundamental lasers having a wide range of fundamental wavelength bandwidths (i.e., the need for expensive “custom-built” fundamental lasers having a specific narrow fundamental wavelength bandwidth is avoided). In addition, by utilizing the frequency conversion module to extract signal light having the usable second wavelength from the broad “rejected” first portion of the fundamental frequency, and to direct the signal light into the frequency mixing module for mixing with the second portion, the present invention also minimizes energy loss by effectively “recycling” usable portions of the first (“rejected”) portion of the fundamental frequency. The resulting sum (output) wavelength is therefore efficiently produced from a broad fundamental wavelength bandwidth having a much narrower wavelength bandwidth than could be produced using conventional techniques (e.g., harmonic conversion and frequency mixing).

[0014] In another embodiment, the DUV laser includes a fundamental laser, a frequency conversion module, a harmonic conversion module, a frequency mixing module, and an optical bandwidth filtering device. The fundamental laser generates a fundamental wavelength with a fundamental wavelength bandwidth. The frequency conversion module converts a first portion of the fundamental wavelength to a second wavelength. The harmonic conversion module generates a harmonic wavelength from a second portion of the fundamental wavelength. The frequency mixing module mixes the second wavelength with the harmonic wavelength to generate a sum wavelength. The optical bandwidth filtering device selects the first and second portions from the fundamental wavelength such that the second portion comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

[0015] In yet another embodiment, the DUV laser includes a fundamental laser, a frequency conversion module, a harmonic conversion module, a frequency mixing module, and an optical bandwidth filtering device. The fundamental laser generates a fundamental wavelength with a fundamental wavelength bandwidth. The frequency conversion module converts a first portion of the fundamental wavelength to a second wavelength. The harmonic conversion module generates a harmonic wavelength from the second wavelength. The frequency mixing module mixes the harmonic wavelength with a second portion of the fundamental wavelength to generate a sum wavelength. The optical bandwidth filtering device selects the first and second portions from the fundamental wavelength such that the second portion comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

[0016] According to an aspect of the invention, the optical bandwidth filtering device is positioned outside of the laser oscillator cavity of the fundamental laser. The optical bandwidth filtering device may include at least one device selected from a group consisting of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter, and an optical grating. The frequency conversion module may include at least one device selected from a group consisting of an optical parametric oscillator (OPO), an optical parametric amplifier (OPA), and a Raman amplifier. The second wavelength may be generated as signal light from the OPO or the OPA. In one embodiment, the fundamental laser comprises a diode laser generating a wavelength of approximately 405 nm or shorter. In another embodiment, the fundamental laser may comprise a fiber laser, a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, or a Nd-doped vanadate laser. In one embodiment, the sum wavelength is approximately equal to 193 nm. In another embodiment the sum wavelength is approximately equal to 184 nm.

[0017] A method of generating deep UV laser radiation is described. In one embodiment, the method includes generating a fundamental laser light having a fundamental wavelength and a fundamental wavelength bandwidth, converting a first portion of the fundamental wavelength to a second wavelength, generating a harmonic wavelength from a second portion of the fundamental wavelength, and summing the second wavelength and the harmonic wavelength to generate an output wavelength. Notably, the second portion of the fundamental wavelength comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

[0018] Another method of generating deep UV laser radiation is described. In one embodiment, this method includes generating a fundamental laser light having a fundamental wavelength and a fundamental wavelength bandwidth, converting a first portion of the fundamental wavelength to a second wavelength, and summing the second wavelength and a second portion of the harmonic wavelength to generate an output wavelength. Notably, the second portion of the fundamental wavelength comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

[0019] Yet another method of generating deep UV laser radiation is described. In one embodiment, this method includes generating a fundamental laser light having a fundamental wavelength and a fundamental wavelength bandwidth, converting a first portion of the fundamental wavelength to a second wavelength, generating a harmonic wavelength from the second wavelength, and summing a second portion of the fundamental wavelength and the harmonic wavelength to generate an output wavelength. Notably, the second portion of the fundamental wavelength comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

[0020] With respect to these methods, selecting of the first and second portions may be performed by at least one of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter, or an optical grating. Notably, such optical bandwidth filtering devices, in effect, direct one range of wavelengths into one portion of a frequency conversion chain and another range of wavelengths into another portion of the frequency conversion train, thereby substantially reducing the power loss compared with lasers that use the optical bandwidth filtering devices to reduce the bandwidth by simply rejecting unwanted wavelengths. Furthermore, by placing the bandwidth narrowing devices outside the laser cavity, some or all of the detrimental effects of intra-cavity bandwidth-controlling devices can be avoided. Laser parameters other than the bandwidth can be largely maintained without redesigning the laser oscillator cavity. Converting the first portion of the fundamental wavelength to the second wavelength may be performed by an OPO, an OPA, or a Raman amplifier. Generating the fundamental laser light may be performed by one of diode laser, a Nd:YAG laser, an Nd-doped vanadate laser, and an Yb-doped fiber laser.

[0021] An exemplary inspection system is described. This inspection system includes an illumination source, optics, and a detector. The illumination source includes a DUV laser that generates DUV radiation of a desired wavelength and bandwidth. The DUV laser includes an optical bandwidth filtering device, e.g. an etalon, that directs one range of wavelengths into one portion of a frequency conversion chain and another range of wavelengths into another portion of the frequency conversion train. The optics are configured to direct and focus radiation from the illumination source onto a sample. The sample is supported by a stage, which moves relative to the optics during the inspection. The detector is configured to receive reflected or scattered light from the sample, wherein the optics are further configured to collect, direct, and focus the reflected or scattered light onto the detector. The detector includes one or more image sensors. At least one image sensor may be a time delay integration (TDI) sensor.

[0022] The exemplary inspection system may include one or more illumination paths that illuminate the sample from different angles of incidence and/or different azimuth angles and/or with different wavelengths and/or polarization states. The exemplary inspection system may include one or more collection paths that collect light reflected or scattered by the sample in different directions and/or are sensitive to different wavelengths and/or to different polarization states. The exemplary inspection system may include a TDI sensor with readout circuits on two sides that are used to read out two different signals simultaneously. The exemplary inspection system may include an electron-bombarded image or an avalanche image sensor.

[0023] An exemplary method for controlling the bandwidth of a laser and, at the same time, reducing its chirp is described. A bandwidth controlling device is placed outside the laser oscillator cavity. Under certain circumstances, after bandwidth filtering, a chirped pulse can be converted to a closer-to-transform-limited pulse with narrower bandwidth and shorter pulse length. This is highly desirable for higher conversion efficiency in nonlinear frequency conversion.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] Figure 1 illustrates an exemplary inspection system incorporating an illumination source that comprises a DUV laser providing optimized bandwidth control.

[0025] Figures 2A and 2B illustrate exemplary inspection systems using line illumination with one, or more, collection channels and a DUV laser providing optimized bandwidth control.

[0026] Figure 3 illustrates an exemplary inspection system including a DUV laser providing normal and oblique illumination as well as optimized bandwidth control

[0027] Figure 4 illustrates an exemplary inspection system with bright-field and dark-field illumination channels. The DUV laser in this inspection system, used for the dark-field illumination channel, provides optimized bandwidth control.

[0028] Figure 5 illustrates an exemplary inspection system incorporating a split-readout image sensor and an illumination source comprising a DUV laser providing optimized bandwidth control.

[0029] Figure 6A illustrates an exemplary DUV laser including an optical bandwidth filtering device, e.g. an etalon, to control the bandwidth.

[0030] Figure 6B illustrates an alternate exemplary DUV laser including an optical bandwidth filtering device, e.g. an etalon, to control the bandwidth.

[0031] Figure 6C illustrates another exemplary DUV laser including an optical bandwidth filtering device, e.g. an etalon, to control the bandwidth.

[0032] Figure 7 illustrates an exemplary pulse width shortening after bandwidth filtering.

DETAILED DESCRIPTION OF THE DRAWINGS

[0033] Figure 1 illustrates an exemplary inspection system 100 configured to measure a sample 108 such as a wafer, reticle, or photomask. Sample 108 is placed on a stage 112 in order to facilitate movement to different regions of sample 108 underneath the optics. Stage 112 may comprise an X-Y stage or an R-θ stage. In some embodiments, stage 112 can adjust the height of sample 108 during inspection to maintain focus. In other embodiments, an objective lens 105 can be adjusted to maintain focus.

[0034] An illumination source 102 may comprise one or more lasers and/or a broad-band light source. Illumination source 102 may emit DUV and/or VUV radiation. Illumination source 102 includes one of the DUV lasers incorporating bandwidth control that is described herein. Optics 103 including an objective lens 105 directs that radiation towards, and focuses it on, sample 108. Optics 103 may also comprise mirrors, lenses, and/or beam splitters. Light reflected or scattered from sample 108 is collected, directed, and focused by optics 103 onto a detector 106, which is within a detector assembly 104. Detector 106 may include a two-dimensional array sensor or a one-dimensional line sensor. In one embodiment, the output of detector 106 is provided to a computing system 114, which analyzes the output. Computing system 114 is configured by program instructions 118, which can be stored on a carrier medium 116.

[0035] One embodiment of inspection system 100 illuminates a line on sample 108, and collects scattered and/or reflected light in one or more dark-field and/or bright-field collection channels. In this embodiment, the detector 106 may include a line sensor or an electron-bombarded line sensor.

[0036] Another embodiment of inspection system 100 illuminates multiple spots on sample 108, and collects scattered and/or reflected light in one or more dark-field and/or bright-field collection channels. In this embodiment, detector 106 may include a two-dimensional array sensor or an electron-bombarded two-dimensional array sensor.

[0037] Additional details of various embodiments of inspection system 100 can be found in U.S. Patent Application 13/554,954, entitled "Wafer Inspection System", and filed on July 9, 2012, U.S. Patent 7,957,066, entitled “Split Field Inspection System Using Small Catadioptric Objectives”, and issued on June 7, 2011, U.S. Patent 7,345,825, entitled “Beam Delivery System For Laser Dark-Field Illumination In A Catadioptric Optical System”, and issued on March 18, 2008, U.S. Patent 5,999,310, entitled “Ultra-Broadband UV Microscope Imaging System With Wide Range Zoom Capability”, and issued on December 7, 1999, and U.S. Patent 7,525,649, entitled “Surface Inspection System Using Laser Line Illumination With Two Dimensional Imaging”, which issued on April 28, 2009. These patents and patent applications are incorporated by reference herein.

[0038] Figures 2A and 2B illustrate aspects of dark-field inspection systems that incorporate the DUV lasers and/or methods described herein. For example, in Figure 2A, illumination optics 201 comprises a DUV laser system 220 for generating light 202 that is focused by a mirror or a lens 203 into a line 205 on the surface of a sample 211 being inspected. DUV laser system 220 includes the DUV laser described herein, which can provide optimized bandwidth control. Collection optics 210 directs light scattered from line 205 to a sensor 215 using lenses and/or mirrors 212 and 213. An optical axis 214 of the collection optics is not in the illumination plane of line 205. In some embodiments, axis 214 is approximately perpendicular to line 205. Sensor 215 may comprise an array sensor, such as a linear array sensor.

[0039] Figure 2B illustrates one embodiment including multiple dark-field collection systems 231, 232 and 233, each system being substantially similar to the collection optics 210 of Figure 2A. Collection systems 231, 232 and 233 are used in combination with illumination optics substantially similar to illumination optics 201 in Figure 2A. In this embodiment, sample 211 is supported on a stage 221, which moves the areas to be inspected underneath the optics. Stage 221 may comprise an X-Y stage or an R-θ stage, which preferably moves substantially continuously during the inspection in order to inspect large areas of the sample with minimal dead time.

[0040] More details of inspection systems in accordance with the embodiments illustrated in Figures 2A and 2B can be found in U.S. Patent 7,525,649, entitled “Surface

Inspection System Using Line Illumination With Two Dimensional Imaging", and issued April 28, 2009. U.S. Patent 6,608,676, entitled "System For Detecting Anomalies And/Or Features Of A Surface", and issued August 19, 2003 also describes line illumination systems suitable for inspection of unpatterned or patterned wafers. These patents are incorporated by reference herein.

[0041] Figure 3 illustrates an inspection system 300 configured to detect particles or defects on a sample using both normal and oblique illumination beams. In this configuration, a DUV laser system 330 provides a laser beam 301. DUV laser system 330 includes the DUV laser described herein, which provides optimized bandwidth control. A lens 302 focuses the beam 301 through a spatial filter 303. Lens 304 collimates the beam and conveys it to a polarizing beam splitter 305. Beam splitter 305 passes a first polarized component to the normal illumination channel and a second polarized component to the oblique illumination channel, where the first and second components are orthogonal. In the normal illumination channel 306, the first polarized component is focused by optics 307 and reflected by mirror 308 towards a surface of a sample 309. The radiation scattered by sample 309 (such as a wafer or photomask) is collected and focused by a paraboloidal mirror 310 to a sensor 311.

[0042] In the oblique illumination channel 312, the second polarized component is reflected by beam splitter 305 to a mirror 313 which reflects such beam through a half-wave plate 314 and focused by optics 315 to sample 309. Radiation originating from the oblique illumination beam in the oblique channel 312 and scattered by sample 309 is also collected by paraboloidal mirror 310 and focused to sensor 311. The sensor and the illuminated area (from both the normal and oblique illumination channels form surface 309) are preferably at the foci of paraboloidal mirror 310.

[0043] Paraboloidal mirror 310 collimates the scattered radiation from sample 309 into a collimated beam 316. Collimated beam 316 is then focused by an objective 317 and through an analyzer 318 to sensor 311. Note that curved mirrored surfaces having shapes other than paraboloidal shapes may also be used. An instrument 320 can provide relative motion between the beams and sample 309 so that spots are scanned across the surface of sample 309. U.S. Patent 6,201,601, entitled “Sample Inspection System”, and issued on March 13, 2001 describes inspection system 300 in further detail. This patent is incorporated by reference herein.

[0044] Figure 4 illustrates an exemplary catadioptric imaging system 400 configured as an inspection system with bright-field and dark-field inspection modes. System 400 may incorporate two illuminations sources: a laser 401, and a broad-band light illumination module 420. In one embodiment, laser 401 may include a DUV laser described herein, which provides optimized bandwidth control.

[0045] In a dark-field mode, adaptation optics 402 control the laser illumination beam size and profile on the surface being inspected. Mechanical housing 404 includes an aperture and window 403, and a prism 405 to redirect the laser along the optical axis at normal incidence to the surface of a sample 408. Prism 405 also directs the specular reflection from surface features of sample 408 out of objective 406. Objective 406 collects light scattered by sample 408 and focuses it on a sensor 409. Lenses for objective 406 can be provided in the general form of a catadioptric objective 412, a focusing lens group 413, and a tube lens section 414, which may, optionally, include a zoom capability.

[0046] In a bright-field mode, broad-band illumination module 420 directs broad-band light to beam splitter 410, which reflects that light towards focusing lens group 413 and catadioptric objective 412. Catadioptric objective 412 illuminates the sample 408 with the broadband light. Light that is reflected or scattered from sample 408 is collected by objective 406 and focused on sensor 409. Broad-band illumination module 420 comprises, for example, a laser-pumped plasma light source or an arc lamp. Broad-band illumination module 420 may also include an auto-focus system to provide a signal to control the height of sample 408 relative to catadioptric objective 412. U.S. Patent 7,345,825, entitled “Beam Delivery System For Laser Dark-Field Illumination In A

Catadioptric Optical System", issued on March 18, 2008, and incorporated by reference herein, describes system 400 in further detail.

[0047] Figure 5 illustrates a reticle, photomask, or wafer inspection system 500 that simultaneously detects two channels of image or signal on one sensor 570. Image sensor 570 comprises a split-readout image sensor. Illumination source 509 includes a DUV laser as described herein, which provides optimized bandwidth control. The operating wavelength of this DUV laser may be shorter than 200 nm, such as a wavelength of approximately 193 nm. The two channels may comprise reflected and transmitted intensity when an inspected object 530 is transparent (for example a reticle or photomask), or may comprise two different illumination modes, such as angles of incidence, polarization states, wavelength ranges, or some combination thereof. The light is directed to inspected object 530 using channel one illumination relay 515 as well as channel two illumination relay 520.

[0048] Inspected object 530 may be a reticle, a photomask, or a semiconductor wafer to be inspected. Image relay optics 540 can direct the light that is reflected and/or transmitted by inspected object 530 to a channel one image mode relay 555 and to a channel two image mode relay 560. Channel one image mode relay 555 is tuned to detect the reflection or transmission corresponding to channel one illumination relay 515, whereas channel two image mode relay sensor 560 is tuned to detect the reflection or transmission corresponding to channel two illumination relay 520. Channel one image mode relay 555 and channel two image mode relay 560 in turn direct their outputs to a sensor 570. The data corresponding to the detected signals or images for the two channels is shown as data 580 and may be transmitted to a computer (not shown) for processing.

[0049] Other details of reticle and photomask inspection systems and methods that may be configured to measure transmitted and reflected light from a reticle or photomask are described in U.S. Patent 7,352,457, entitled "Multiple Beam Inspection Apparatus And Method", issued on April 1, 2008, and in U.S. Patent 5,563,702, entitled "Automated

Photomask Inspection Apparatus And Method", issued on October 8, 1996, both of which are incorporated by reference herein.

[0050] Additional details regarding exemplary embodiments of image sensor 570 are provided in U.S. Patent Application 14/096,911, entitled "Method And Apparatus For High Speed Acquisition Of Moving Images Using Pulsed Illumination", filed on December 4, 2013, and in U.S. Patent 7,528,943, entitled "Method And Apparatus For Simultaneous High-Speed Acquisition Of Multiple Images", issued May 5, 2009, both of which are incorporated by reference herein

[0051] Figure 6A illustrates an exemplary DUV laser 600 configured to provide optimized bandwidth control. An optical parametric oscillator (OPO) or optical parametric amplifier (OPA) 604 is employed in the system. Taking advantage of the wavelength tunability in OPO/OPA 604, DUV laser 600 can generate output light at a chosen specific wavelength, i.e. a wavelength which may or may not be equal to an integer harmonic of the fundamental laser. Notably, the bandwidth of fundamental light 602 (generated by fundamental laser 601) can be narrowed by passing through an etalon 603 (see, e.g. arrows 611A and 611B). Etalon 603 preferably has high transmission over a narrow range of wavelengths centered close to the center wavelength of the fundamental light 602, so that the light transmitted through the etalon, narrowed fundamental 602', has a narrower bandwidth than the fundamental 602. Narrowed fundamental light 602' is directed to a harmonic conversion module 607, which generates an n^{th} harmonic ($n\omega$) 608, which is typically a DUV wavelength. Note that the n^{th} harmonic 608 has a narrower bandwidth than would result from providing fundamental 602 to harmonic conversion module 607 directly.

[0052] Since etalon 603 reflects most of the incident energy at wavelengths that it does not transmit, as shown in Figure 6A, an out-of-band rejected fundamental 602" has a broad bandwidth with a dip in the middle of its spectrum. This rejected light 602", which would otherwise be wasted, can be used as a pump light for OPO/OPA 604. As a result of energy conservation in nonlinear parametric process, OPO/OPA 604 can still generate a narrow bandwidth signal light 605 from the broadband pump light of rejected fundamental 602" at the expense of generating a broad bandwidth idler light 606, which has a similar dip in the middle of its spectrum, but a broader bandwidth than rejected fundamental 602". However, because idler light 606 is not used in the laser, this idler light 606 has no significant effect on the laser performance. The bandwidth of signal light 605 is determined by a seed laser or by a wavelength selective element, such as a volume-Bragg grating, in OPO/OPA 604.

[0053] In one embodiment, a Raman amplifier can replace OPO/OPA 604. Because the bandwidth of an amplified signal light generated by the Raman amplifier is independent of the bandwidth of its pump light (it typically depends on wavelength selective elements in the Raman amplifier), a Raman amplifier can also generate signal light 605 with a desired narrow bandwidth.

[0054] A frequency mixing module 609 can generate a laser output 610 by summing the frequencies of the n^{th} harmonic 608 ($n\omega$) and the signal light 605 (ωs). Because the bandwidth of the n^{th} harmonic 608 has been reduced by etalon 603 and the bandwidth of signal light 605 is determined by OPO/OPA 604, the bandwidth of laser output 610 is narrower than it would be in an otherwise identical laser that does not incorporate etalon 603 (that is, bandwidth indicated by arrow 611A would be used instead of bandwidth indicated by arrow 611B). This reduced bandwidth is achieved with minimal power losses since etalon 603 reflects most of the energy that it does not transmit.

[0055] In one exemplary embodiment, fundamental laser 601 may operate at a wavelength of approximately 1064 nm using, for example, a Nd:YAG (neodymium-doped yttrium aluminum garnet) or Nd-doped vanadate laser. In this case, harmonic conversion module 607 may generate a fifth harmonic 608 (5ω) of approximately 213 nm, OPO/OPA module 604 may generate signal light 605 having a wavelength of approximately 2108 nm, and frequency mixing module 609 may generate laser output 610 having a wavelength of approximately 193 nm by mixing the 213 nm and 2108 nm wavelengths. The wavelength of approximately 193 nm is a useful wavelength for inspecting semiconductor photomasks and wafers.

[0056] In another exemplary embodiment, the fundamental laser 601 may operate at a wavelength of approximately 1064 nm using, for example, a Nd:YAG or Nd-doped vandate laser. In this case, harmonic conversion module 607 may generate a fourth harmonic 608 (4ω) of approximately 266 nm, OPO/OPA module 604 may generate signal light 605 having a wavelength of approximately 1416 nm, and frequency mixing module 609 first mixes 266 nm and 1416 nm wavelengths to create a sum wavelength of approximately 224 nm, then remixes the sum wavelength of approximately 224 nm with the 1416 nm wavelength signal light 605 to generate a laser output 610 of wavelength approximately 193 nm.

[0057] In yet another exemplary embodiment, fundamental laser 601 may operate at a wavelength of approximately 1064 nm using, for example, a Nd:YAG (neodymium-doped yttrium aluminum garnet) or Nd-doped vanadate laser. In this embodiment, harmonic conversion module 607 may generate a fifth harmonic 608 (5ω) of approximately 213 nm, OPO/OPA module 604 may generate signal light 605 having a wavelength of between approximately 1268 nm and approximately 1400 nm, and frequency mixing module 609 may generate laser output 610 having a wavelength of approximately 182.5 nm to approximately 185 nm by mixing the 213 nm and signal wavelengths. The wavelength of approximately 184 nm is a useful wavelength for inspecting semiconductor photomasks and wafers because short wavelengths generally have better sensitivity to smaller features and defects. Furthermore light of approximately 184 nm wavelength can be generated efficiently by this scheme because CLBO is close to non-critically phase matched for such wavelength combinations and so is efficient and stable for the frequency mixing.

[0058] Figure 6B shows an alternate exemplary DUV laser 620 with optimized bandwidth control. The embodiment of DUV laser 620 is similar to that of DUV laser 600 (Figure 6A), except that DUV laser 620 does not include a harmonic conversion module. In DUV laser 620, a frequency mixing module 609B generates a laser output 610B by directly mixing narrowed fundamental 602' and signal light 605. Note that components in

DUV lasers 620 and 600 having the same labels have the same functions and therefore are not be described in reference to Figure 6B. DUV laser 620 is particularly useful when fundamental laser 601 generates a UV wavelength, such as a wavelength of 405 nm or 375 nm. Such wavelengths can be generated, for example, by laser diodes.

[0059] In one exemplary embodiment, fundamental laser 601 may comprise a laser diode operating at a wavelength of approximately 375 nm. In this case, OPO/OPA module 604 may generate signal light 605 having a wavelength of between approximately 607 nm and approximately 750 nm, and frequency mixing module 609 may generate laser output 610 having a wavelength of between approximately 232 nm and approximately 250 nm by mixing the 375 nm and signal wavelengths. This scheme can efficiently and inexpensively generate the output wavelength of between approximately 232 nm and approximately 250 nm because frequency mixing module 609 may use a CLBO crystal for frequency mixing. CLBO is close to non-critically phase matched for such wavelength combinations and so can do the frequency mixing efficiently and stably.

[0060] Figure 6C shows another exemplary DUV laser 630 with optimized bandwidth control. This embodiment of DUV laser 630 is similar to that of DUV laser 600 (Figure 6A), with the following exceptions. In this case, a harmonic conversion module 607C is used to generate an n^{th} signal harmonic 608C ($n\omega s$) of signal light 605. Additionally, a frequency mixing module 609C generates a laser output 610C by mixing narrowed fundamental 602' and n^{th} signal harmonic 608C. Note that components in DUV lasers 630 and 600 having the same labels have the same functions and therefore are not be described in reference to Figure 6C. The embodiment of DUV 630 is particularly useful when the wavelength of laser output 610C cannot be achieved with a specific fundamental laser (for example, because the available non-linear crystals for frequency mixing module 609 or harmonic conversion module 607 (DUV laser 600, Figure 6A) cannot phase match for one or more of the wavelengths). DUV laser 630 can provide different wavelength combinations for frequency mixing module 609C and harmonic conversion module 607C and can, in some cases, provide a viable way to generate the desired laser output wavelength when the embodiment of DUV 600 (Figure 6A) cannot.

[0061] In one exemplary embodiment, fundamental laser 601 may operate at a wavelength of approximately 800 nm using, for example, a Ti-sapphire laser. In this case, OPO/OPA module 604 may generate signal light 605 (ωs) having a wavelength between approximately 888 nm and 1080 nm, harmonic conversion module 607 may generate a third harmonic 608 (3ωs) of between approximately 296 nm and 360 nm, and frequency mixing module 609 may generate laser output 610 having a wavelength of between approximately 216 nm and 248 nm by mixing the third harmonic and the approximately 800 nm wavelengths.

[0062] Figure 7 illustrates how pulse width shortening is possible by bandwidth filtering. Laser pulses generated by mode-locked or modulated laser oscillators usually have approximately Gaussian spectral shapes and exhibit approximately linear chirp. “T0” is the transform-limited pulse width of a pulse with the same bandwidth as the chirped pulse; “T” is the pulse width before bandwidth reduction; and “T’” is the pulse width after bandwidth reduction. A bandwidth reduction ratio is defined as the pulse bandwidth after filtering (i.e. after passing through the etalon) divided by the pulse bandwidth before filtering. In Figure 7, the case without bandwidth reduction, i.e. T’ = T, is plotted as a solid line 701 for reference. Points above line 701 represent cases where the pulse width increases, i.e. T’ > T. Points below line 701 represent cases where the pulse width decreases, i.e. T’ < T. Two cases of different bandwidth reduction ratios (0.6 and 0.8) are illustrated by dashed line 702 and dotted line 703 respectively.

[0063] Figure 7 shows that under certain circumstances, bandwidth reduction of a chirped pulse would result in a shorter pulse, which is closer to transform-limited. For example, for the 0.6 bandwidth reduction ratio, when the pulse width T is greater than about 2 T0, reducing the bandwidth shortens the pulse width. In another example, for the 0.8 bandwidth reduction ratio, when the pulse width T is greater than about 1.6 T0, the pulse width is reduced when the bandwidth is reduced. As explained above, reducing the pulse width helps maintain the efficiency of the harmonic conversion and frequency mixing processes. Note that when the initial pulse width is close to T0, i.e. the initial pulse is close to transform limited, then any bandwidth reduction necessarily increases the pulse width.

[0064] The lines plotted in Figure 7 were calculated for Gaussian pulse shapes. Other common laser pulse shapes such as sech^2 pulses show the same trends. See, for example, Agrawal, "Nonlinear Fiber Optics", 4th ed, pp54-59, Academic Press, 2007.

[0065] A typical high powered laser (such as a laser with an output of about 30W or more) has a pulse width significantly longer than a transform-limited pulse of the same bandwidth. As a result, the various methods and DUV lasers disclosed herein are particularly useful for generating narrow bandwidth DUV laser output light at powers of about 100 mW or more while maintaining good conversion efficiency.

[0066] More detailed descriptions of 193 nm lasers that can benefit from the optimized bandwidth control of the DUV lasers described herein are provided by U.S. Patent Application 13/ 797,939, entitled "Solid-state 193 nm laser and an inspection system using a solid-state 193 nm laser", and filed on March 12, 2013, U.S. Provisional Patent Application 61/756,209, entitled "193 nm laser using OPO and an inspection system using a 193 nm laser", and filed on January 24, 2013, and U.S. Provisional Patent Application 61/764,441, entitled "193 nm laser using 1109 nm", and filed on February 13, 2013. All of these applications are incorporated by reference herein.

[0067] Note that the above-described DUV lasers can be operated at other wavelengths shorter than about 200 nm by appropriate selection of the wavelength of the signal light ωs and appropriate changes to the frequency mixing module (i.e. frequency mixing modules 609, 609B or 609C). In particular, vacuum UV wavelengths shorter than 190 nm can be generated by such lasers.

[0068] Exemplary embodiments of image sensors suitable for use in an inspection or imaging system incorporating any of the DUV lasers described herein can be found in

U.S. Published Patent Application 2013/0264481, entitled “Back-Illuminated Sensor With Boron Layer”, which published on October 10, 2013 and is incorporated by reference herein.

[0069] The above description is presented to enable one of ordinary skill in the art to make and use the invention as provided in the context of a particular application and its requirements. As used herein, directional terms such as “top”, “bottom”, “over”, “under”, “upper”, “upward”, “lower”, “down” and “downward” are intended to provide relative positions for purposes of description, and are not intended to designate an absolute frame of reference. The various embodiments of the DUV laser having optimized bandwidth control and methods described above are illustrative only and are not intended to limit the scope of the invention.

[0070] Various modifications to the described embodiments will be apparent to those with skill in the art, and the general principles defined herein may be applied to other embodiments. For example, the harmonic conversion modules 607 of Figure 6A and 607C of Figure 6C might generate a second, third, fourth, fifth, sixth or higher harmonic. In another example, an etalon or interferometer may be designed to reflect a narrow range of wavelengths and transmit wavelengths outside that narrow range. Such an optical bandwidth filtering device could be substituted for the etalon 603 of Figures 6A, 6B and 6C with an appropriate change of the layout of the laser. The narrowed fundamental 602’ would be reflected to harmonic conversion module 607, frequency mixing module 609 or frequency mixing module 609C as appropriate, and the rejected fundamental 602” would be transmitted to the frequency conversion module such as OPO/OPA 604.

[0071] Therefore, the DUV lasers and methods described herein are not intended to be limited to the particular embodiments shown and described, but are to be accorded the widest scope consistent with the principles and novel features herein disclosed.

CLAIMS

1. A laser comprising:

a fundamental laser generating a fundamental wavelength with a fundamental wavelength bandwidth;

a frequency conversion module for converting a first portion of the fundamental wavelength to a second wavelength;

a frequency mixing module for mixing the second wavelength with a second portion of the fundamental wavelength to create a sum wavelength; and

an optical bandwidth filtering device for selecting the first portion and the second portion from the fundamental wavelength such that the second portion comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

2. The laser of claim 1, wherein the optical bandwidth filtering device is positioned outside a laser oscillator cavity.

3. The laser of claim 1, wherein the optical bandwidth filtering device includes at least one device selected from a group consisting of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter, and an optical grating.

4. The laser of claim 1, wherein the frequency conversion module includes at least one device selected from a group consisting of an optical parametric oscillator (OPO), an optical parametric amplifier (OPA), and a Raman amplifier.

5. The laser of claim 4, wherein the second wavelength is generated as signal light from the OPO or the OPA.

6. The laser of claim 5, wherein the fundamental laser comprises a diode laser generating a wavelength of approximately 405 nm or shorter.

7. A laser comprising:

a fundamental laser generating a fundamental wavelength with a fundamental wavelength bandwidth;

a frequency conversion module for converting a first portion of the fundamental wavelength to a second wavelength;

a harmonic conversion module for generating a harmonic wavelength from a second portion of the fundamental wavelength;

a frequency mixing module for mixing the second wavelength with the harmonic wavelength to create a sum wavelength; and

an optical bandwidth filtering device for selecting the first portion and the second portion from the fundamental wavelength such that the second portion comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

8. The laser of claim 7, wherein the optical bandwidth filtering device is positioned outside a laser oscillator cavity.

9. The laser of claim 7, wherein the optical bandwidth filtering device includes at least one device selected from a group consisting of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter, and an optical grating.

10. The laser of claim 7, wherein the frequency conversion module includes at least one device selected from a group consisting of an optical parametric oscillator (OPO), an optical parametric amplifier (OPA), and a Raman amplifier.

11. The laser of claim 10, wherein the second wavelength is generated as signal light from the OPO or the OPA.

12. The laser of claim 11, wherein the fundamental laser comprises a fiber laser, a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, or a Nd-doped vanadate laser.

13. The laser of claim 12, wherein the sum wavelength is a wavelength between about 180 nm and 200 nm.

14. A laser comprising:

a fundamental laser generating a fundamental wavelength with a fundamental wavelength bandwidth;

a frequency conversion module for converting a first portion of the fundamental wavelength to a second wavelength;

a harmonic conversion module for generating a harmonic wavelength from the second wavelength;

a frequency mixing module for mixing the harmonic wavelength with a second portion of the fundamental wavelength to create a sum wavelength; and

an optical bandwidth filtering device for selecting the first portion and the second portion from the fundamental wavelength such that the second portion comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

15. The laser of claim 14, wherein the optical bandwidth filtering device is positioned outside of a laser oscillator cavity.

16. The laser of claim 14, wherein the optical bandwidth filtering device includes at least one device selected from a group consisting of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter, and an optical grating.

17. The laser of claim 14, wherein the frequency conversion module includes at least one device selected from a group consisting of an optical parametric oscillator (OPO), an optical parametric amplifier (OPA), and a Raman amplifier.

18. The laser of claim 17, wherein the second wavelength is generated as signal light from the OPO or the OPA.

19. The laser of claim 18, wherein the fundamental laser comprises a fiber laser, a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, or a Nd-doped vanadate laser.

20. The laser of claim 19, wherein the sum wavelength is a wavelength between approximately 180 nm and 200 nm.

21. A method of generating deep UV laser radiation, the method comprising:

generating a fundamental laser light having a fundamental wavelength and a fundamental wavelength bandwidth;

converting a first portion of the fundamental wavelength to a second wavelength;

generating a harmonic wavelength from a second portion of the fundamental wavelength; and

summing the second wavelength and the harmonic wavelength to generate an output wavelength,

wherein the second portion of the fundamental wavelength comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

22. The method of Claim 21, further including selecting the first portion and the second portion from the fundamental wavelength, wherein said selecting is performed by at least one of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter or an optical grating.

23. The method of Claim 21, wherein said converting the first portion of the fundamental wavelength to the second wavelength is performed by an OPO, an OPA, or a Raman amplifier.

24. The method of Claim 21, wherein said generating the fundamental laser light is performed by one of a Nd:YAG laser, an Nd-doped vanadate laser, and an Yb-doped fiber laser.

25. The method of Claim 24, wherein the output wavelength is wavelength between approximately 180 nm and 200 nm.

26. A method of generating deep UV laser radiation, the method comprising:

generating a fundamental laser light having a fundamental wavelength and a fundamental wavelength bandwidth;

converting a first portion of the fundamental wavelength to a second wavelength; and

summing the second wavelength and a second portion of the harmonic wavelength to generate an output wavelength,

wherein the second portion of the fundamental wavelength comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

27. The method of Claim 26, further including selecting the first portion and the second portion from the fundamental wavelength, wherein said selecting is performed by at least one of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter or an optical grating.

28. The method of Claim 26, wherein said converting the first portion of the fundamental wavelength to the second wavelength is performed by an OPO, an OPA, or a Raman amplifier.

29. The method of Claim 26, wherein said generating the fundamental laser light is performed by one of a Nd:YAG laser, an Nd-doped vanadate laser, and an Yb-doped fiber laser.

30. A method of generating deep UV laser radiation, the method comprising:

generating a fundamental laser light having a fundamental wavelength and a fundamental wavelength bandwidth;

converting a first portion of the fundamental wavelength to a second wavelength;

generating a harmonic wavelength from the second wavelength; and summing a second portion of the fundamental wavelength and the harmonic wavelength to generate an output wavelength,

wherein the second portion of the fundamental wavelength comprises a narrower range of wavelengths within the fundamental wavelength bandwidth than the first portion.

31. The method of Claim 30, further including selecting the first portion and the second portion from the fundamental wavelength, wherein said selecting is performed by at least one of an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter or an optical grating.

32. The method of Claim 30, wherein said converting the first portion of the fundamental wavelength to the second wavelength is performed by an OPO, an OPA, or a Raman amplifier.

33. The method of Claim 30, wherein said generating the fundamental laser light is performed by one of a Nd:YAG laser, an Nd-doped vanadate laser, and an Yb-doped fiber laser.

34. A system for inspecting a sample, the system comprising:

an illumination source comprising a UV laser for illuminating the sample, the UV laser including an optical bandwidth filtering device for selecting a first portion from a fundamental wavelength and a second portion from the fundamental wavelength, such that the second portion comprises a narrower range of wavelengths within a fundamental wavelength bandwidth than the first portion;

image relay optics configured to direct light outputs, reflections, or transmissions, of the sample to a first channel image mode relay when the light outputs correspond to the first channel, and to a second channel image mode relay when the light outputs correspond to the second channel; and

a sensor configured to receive relay outputs of the first channel image mode relay and the second channel image mode relay.

35. The system of Claim 34, wherein the optical bandwidth filtering device includes an etalon, an optical dielectric filter, a volume Bragg grating, a birefringence filter, or an optical grating.

36. The system of Claim 34, wherein the sensor includes a semiconductor membrane, the semiconductor membrane including circuit elements formed on a first surface of the semiconductor membrane and a pure boron layer deposited on a second surface of the semiconductor membrane.

37. The inspection system of claim 36, wherein the image sensor further comprises an electron bombarded image sensor.

38. A system for inspecting a sample, the system comprising:

an illumination source including a deep ultraviolet (DUV) laser that generates DUV radiation having a predetermined wavelength and bandwidth, the DUV laser including an optical bandwidth filtering device that directs one range of wavelengths into one portion of a frequency conversion chain and another range of wavelengths into another portion of the frequency conversion train;

optics for directing and focusing radiation from the illumination source onto the sample; and

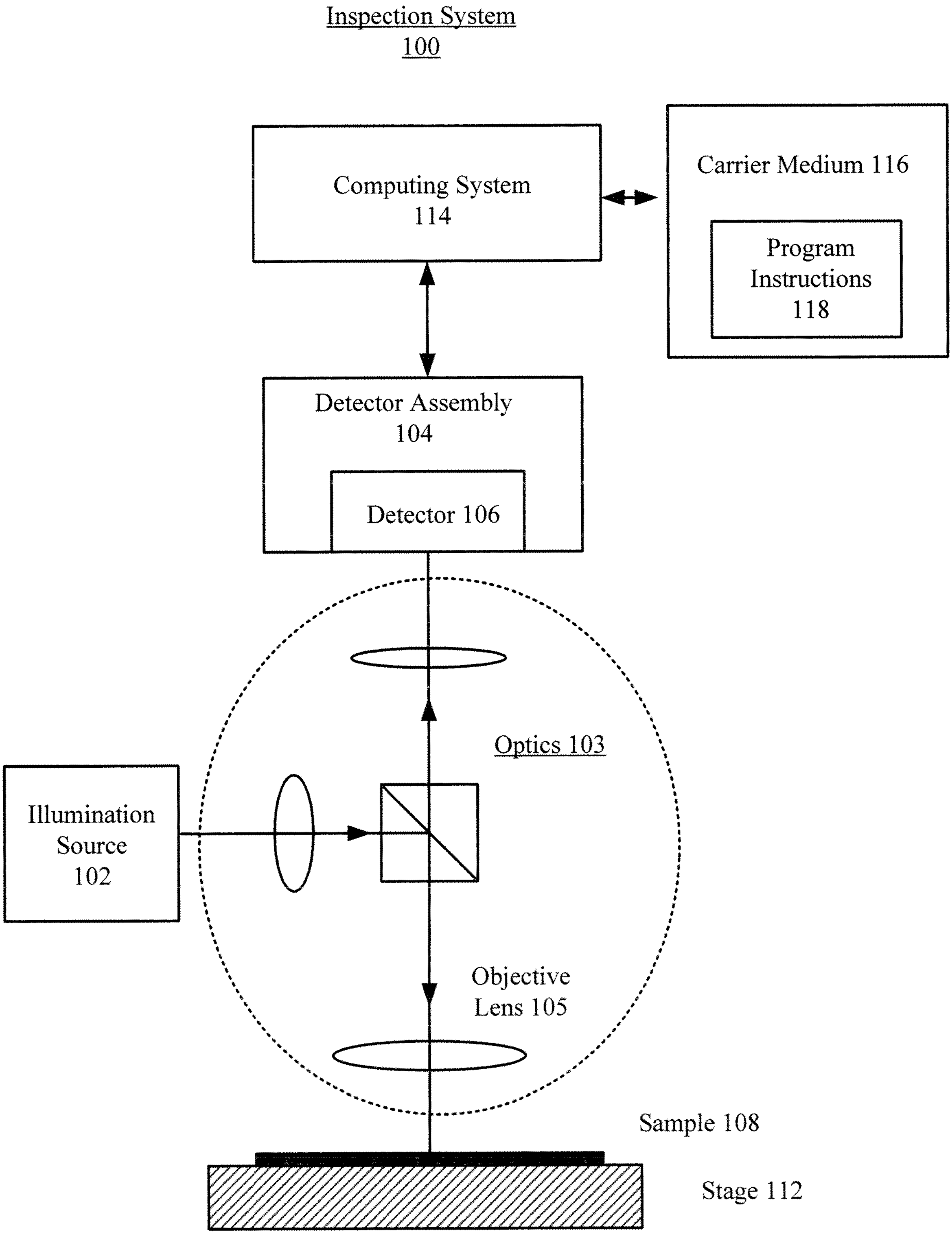
a detector for receiving reflected or scattered light from the sample, wherein the optics are further configured to collect, direct, and focus the reflected or scattered light onto the detector.

39. The system of claim 38, wherein the detector includes one or more image sensors.

40. The system of claim 39, wherein at least one image sensor of the one or more image sensors is a time delay integration (TDI) sensor.

41. The system of claim 38, further including one or more illumination paths that illuminate the sample from different angles of incidence.

42. The system of claim 28, further including one or more collection paths that collect light reflected or scattered by the sample in different directions.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Computing System
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Carrier Medium 116
Program
Instructions
118
Detector Assembly
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Detector 106
Optics 103
Illumination
Source
102
Objective
Lens 105
Sample 108
Stage 112

Figure 1

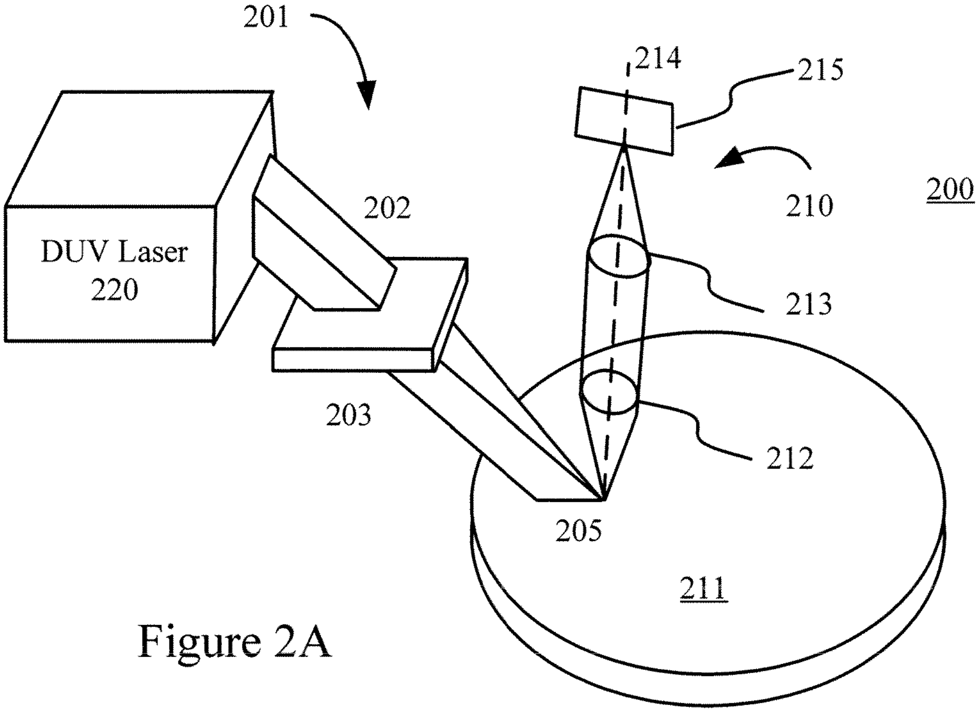

Figure 2A

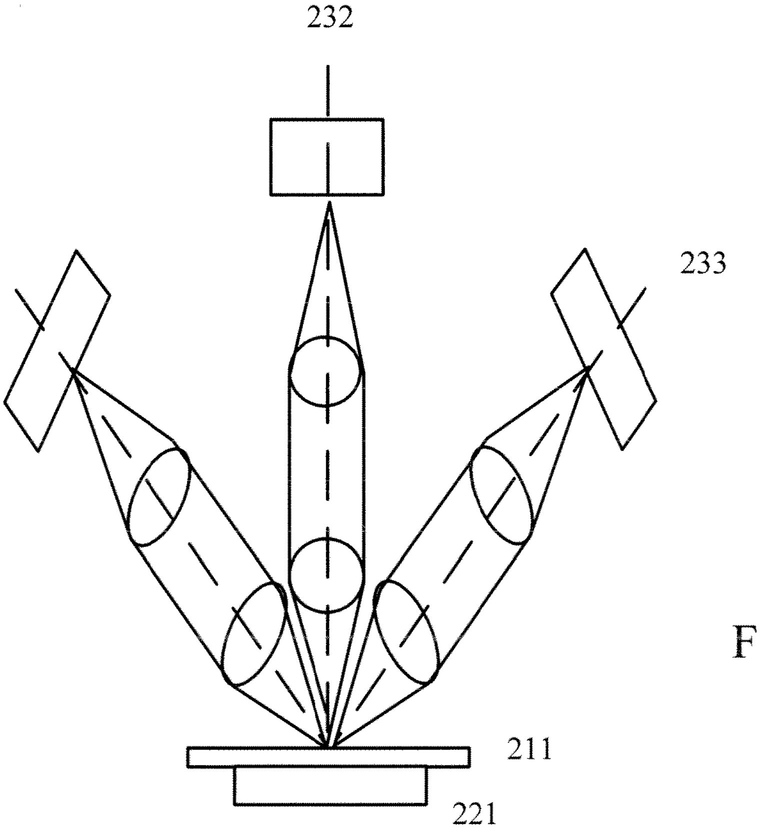

Figure 2B

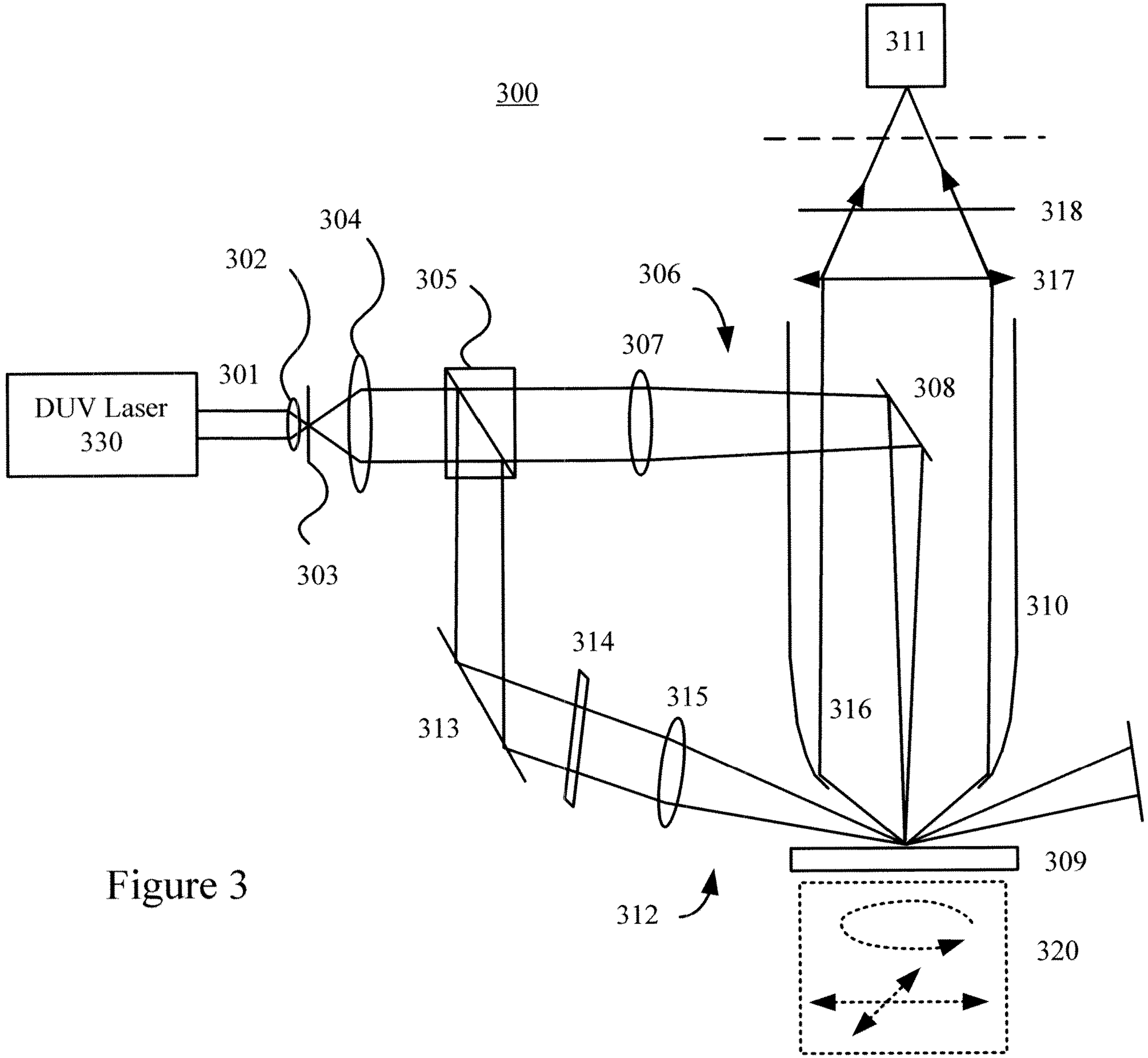
300
311
318
317
304
302
305
306
307
301
308
DUV Laser
330
303
310
314
315
316
313
309
312
320

Figure 3

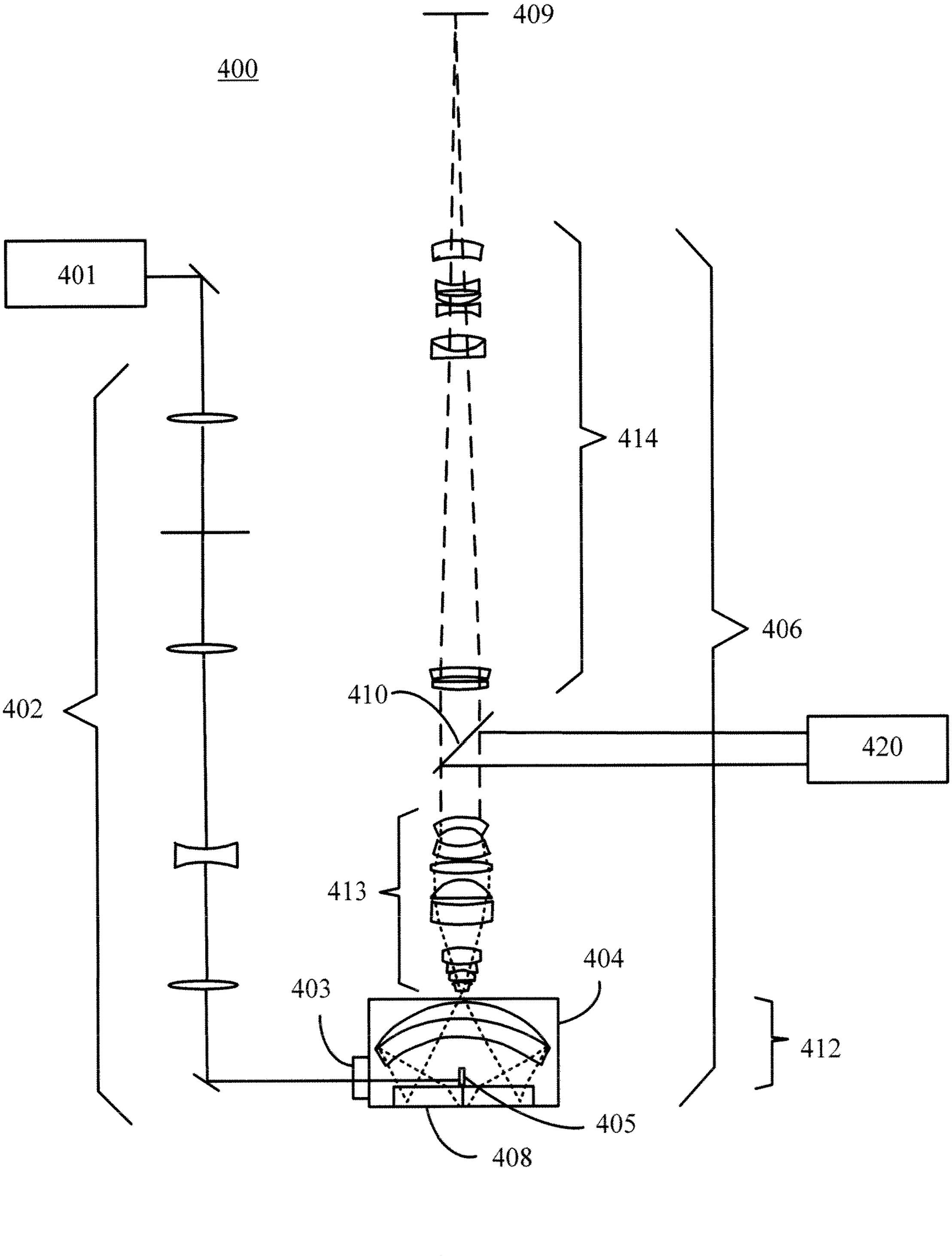

Figure 4

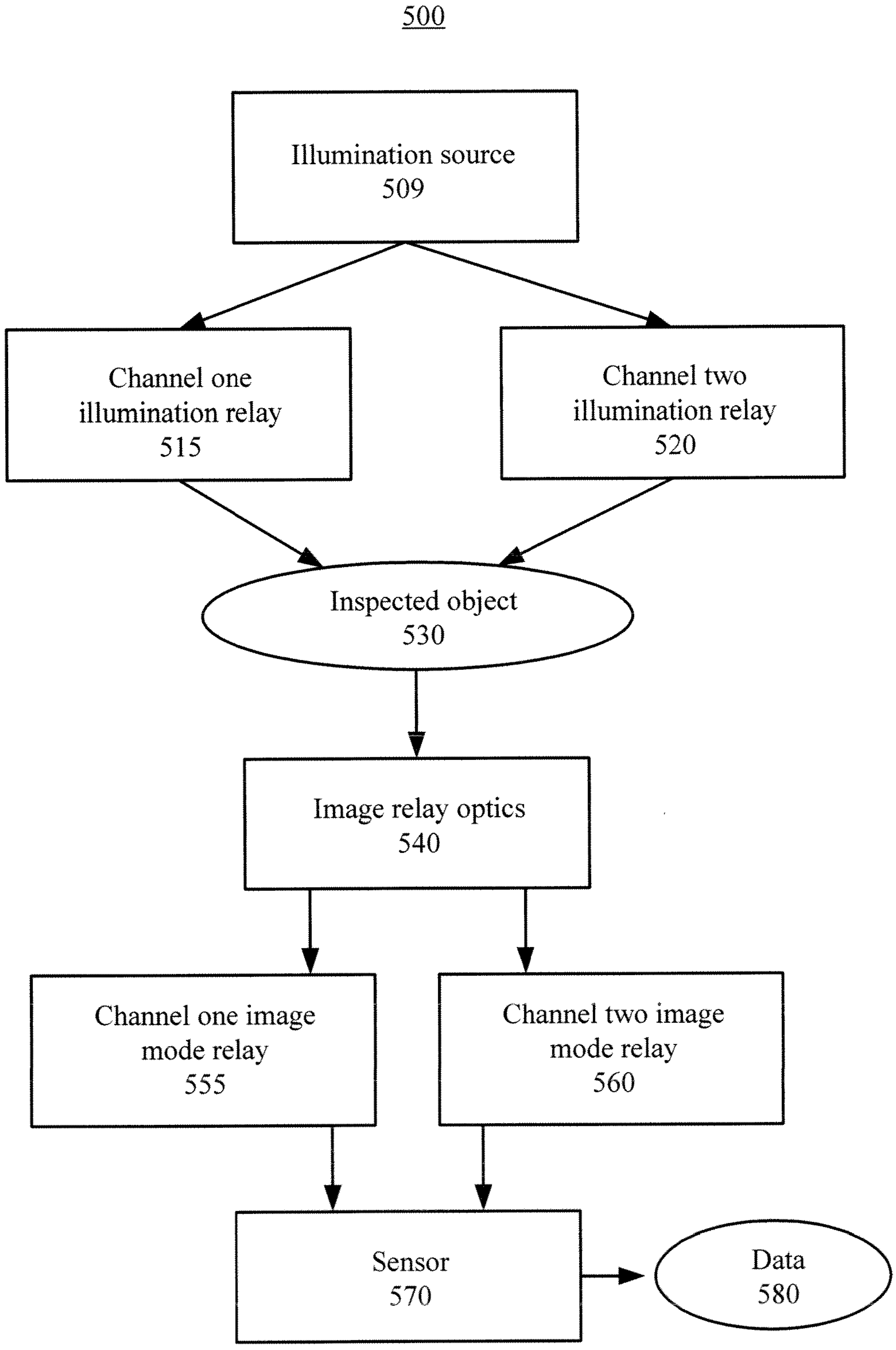
500
Illumination source
509
Channel one illumination relay
515
Channel two illumination relay
520
Inspected object
530
Image relay optics
540
Channel one image mode relay
555
Channel two image mode relay
560
Sensor
570
Data
580

Figure 5

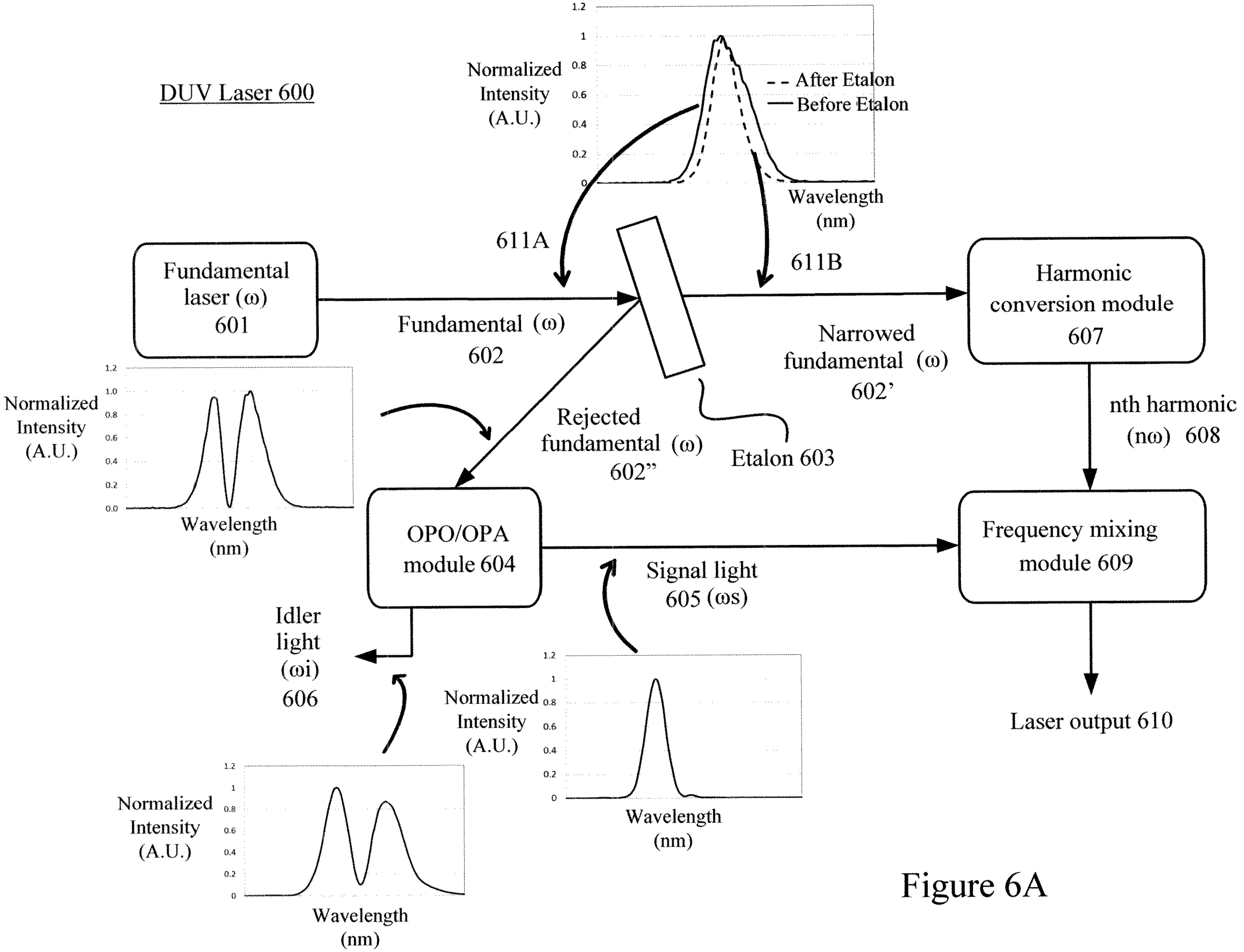
DUV Laser 600
Normalized Intensity (A.U.)
1.2
1
0.8
0.6
0.4
0.2
0
- - After Etalon
— Before Etalon
Wavelength (nm)
611A
611B
Fundamental laser (ω) 601
Fundamental (ω) 602
Narrowed fundamental (ω) 602'
Harmonic conversion module 607
nth harmonic (nω) 608
Rejected fundamental (ω) 602"
Etalon 603
Normalized Intensity (A.U.)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Wavelength (nm)
OPO/OPA module 604
Signal light 605 (ωs)
Frequency mixing module 609
Idler light (ωi) 606
Laser output 610
Normalized Intensity (A.U.)
1.2
1
0.8
0.6
0.4
0.2
0
Wavelength (nm)
Normalized Intensity (A.U.)
1.2
1
0.8
0.6
0.4
0.2
0
Wavelength (nm)

Figure 6A

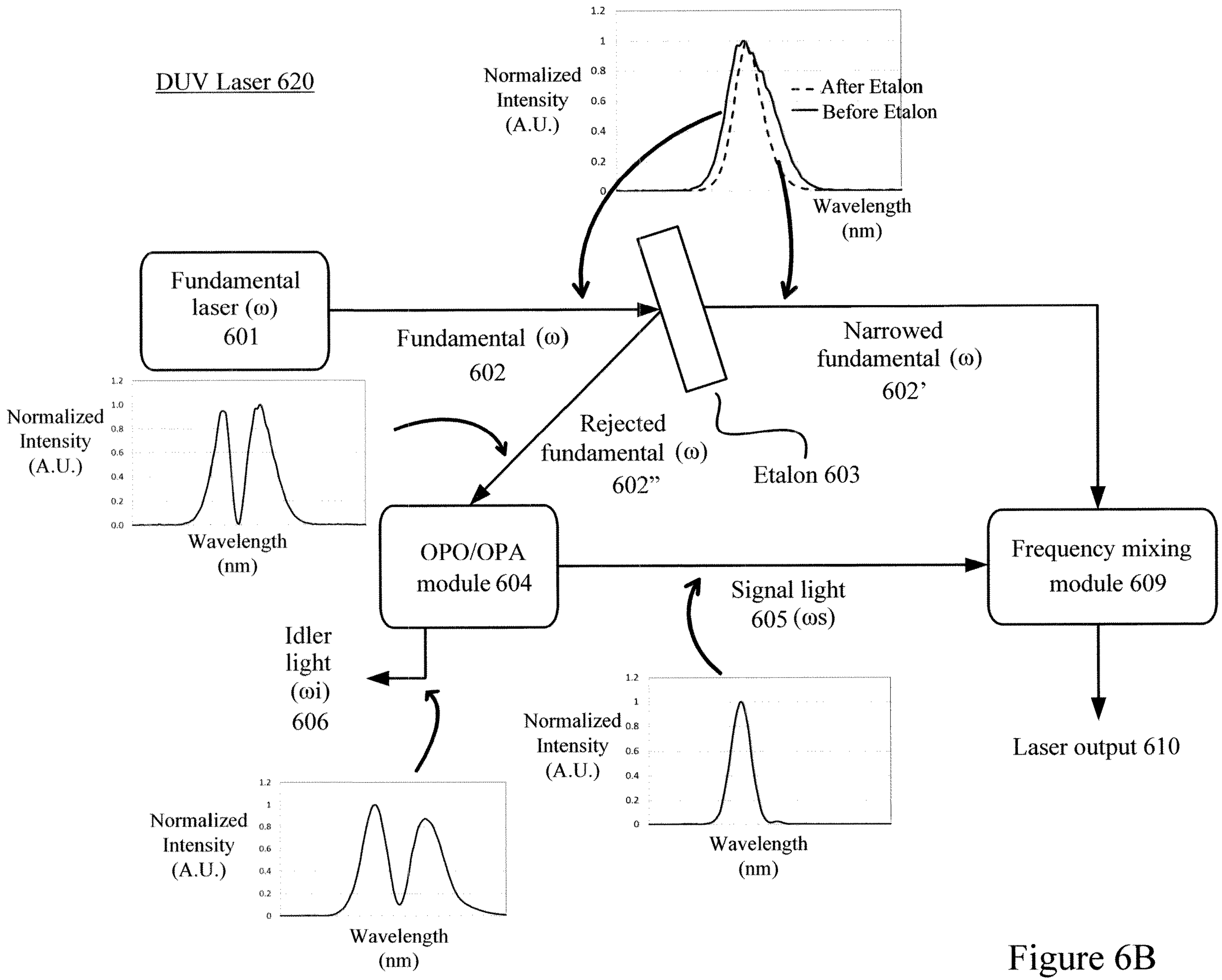
DUV Laser 620
Fundamental laser (ω) 601
Fundamental (ω) 602
Narrowed fundamental (ω) 602'
Rejected fundamental (ω) 602"
Etalon 603
OPO/OPA module 604
Signal light 605 (ωs)
Idler light (ωi) 606
Frequency mixing module 609
Laser output 610
Normalized Intensity (A.U.)
1.2
1
0.8
0.6
0.4
0.2
0
- - After Etalon
— Before Etalon
Wavelength (nm)
Normalized Intensity (A.U.)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Wavelength (nm)
Normalized Intensity (A.U.)
1.2
1
0.8
0.6
0.4
0.2
0
Wavelength (nm)
Normalized Intensity (A.U.)
1.2
1
0.8
0.6
0.4
0.2
0
Wavelength (nm)

Figure 6B

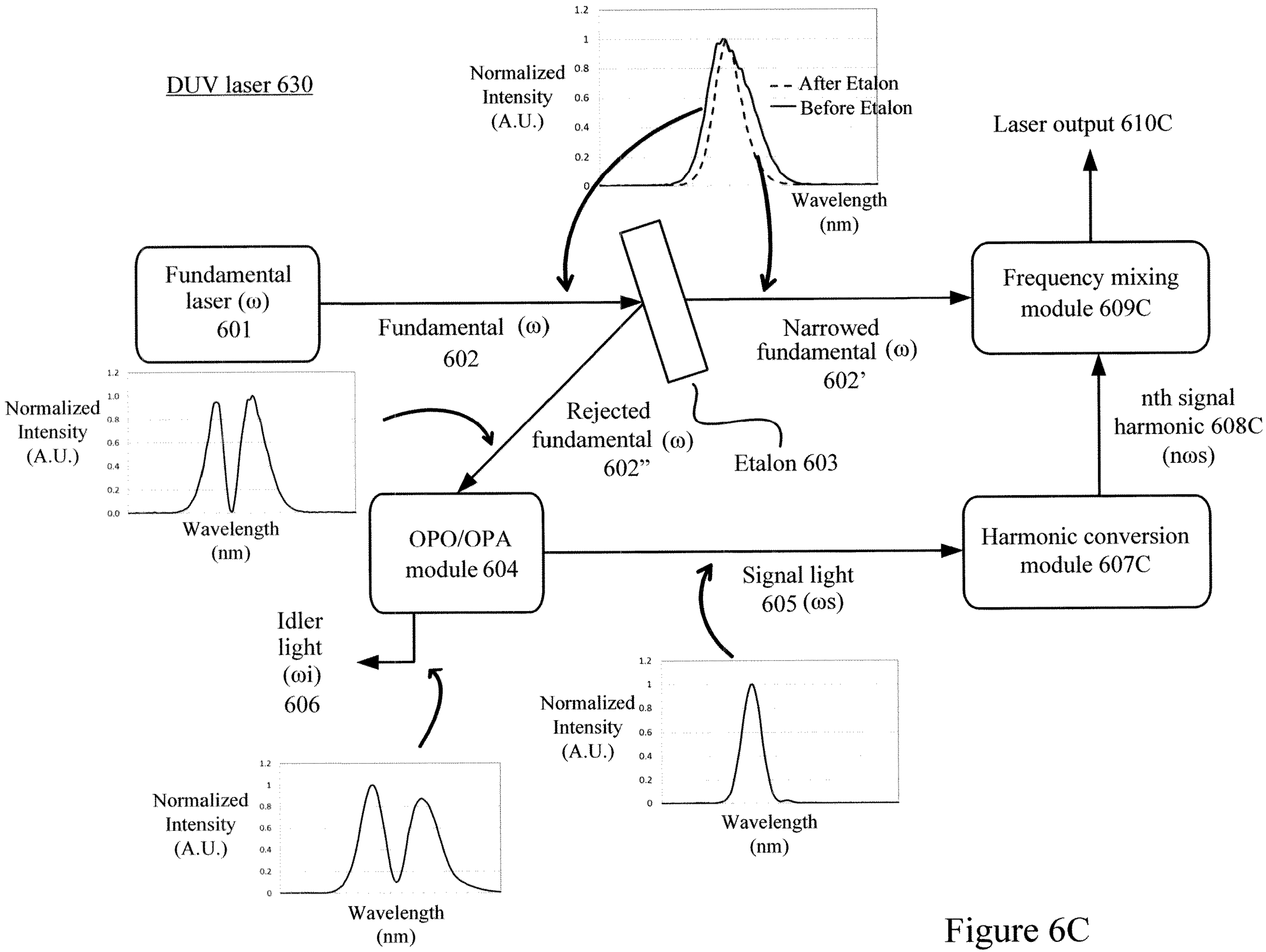
DUV laser 630
Fundamental laser (ω) 601
Fundamental (ω) 602
Normalized Intensity (A.U.)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Wavelength (nm)
- - After Etalon
— Before Etalon
Etalon 603
Narrowed fundamental (ω) 602'
Rejected fundamental (ω) 602"
OPO/OPA module 604
Idler light (ωi) 606
Signal light 605 (ωs)
Harmonic conversion module 607C
nth signal harmonic 608C (nωs)
Frequency mixing module 609C
Laser output 610C

Figure 6C

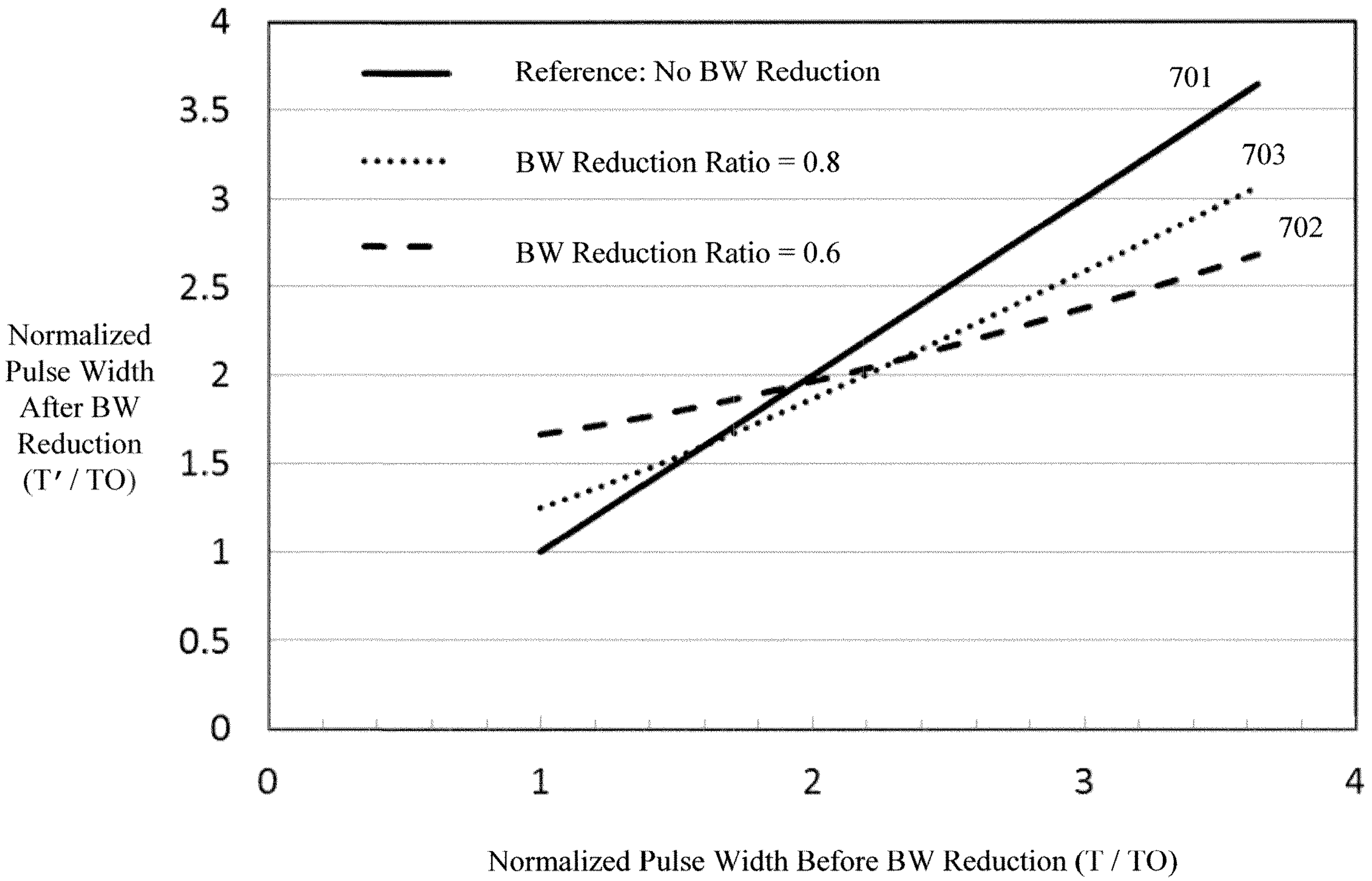
Reference: No BW Reduction
BW Reduction Ratio = 0.8
BW Reduction Ratio = 0.6
701
703
702
Normalized Pulse Width After BW Reduction (T′ / TO)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
Normalized Pulse Width Before BW Reduction (T / TO)

Figure 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/021462

A. CLASSIFICATION OF SUBJECT MATTER

H01S 3/10(2006.01)i, G01N 21/39(2006.01)i

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 3/10; H01S 3/092; H01S 3/30; H01S 3/00; G01N 21/88; G02F 1/355; G02F 1/35; G01N 21/39

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: fundamental laser, wavelength, bandwidth, conversion, mixing, filter, inspection

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013-0313440 A1 (YUNG-HO CHUANG et al.) 28 November 2013 See abstract, paragraphs [0008]-[0012],[0061]-[0123] and figures 1A-9.	1-42
A	US 2012-0026578 A1 (JUN SAKUMA) 02 February 2012 See abstract, paragraphs [0091]-[0099],[0115]-[0119] and figures 1,8.	1-42
A	US 2014-0016655 A1 (J. JOSEPH ARMSTRONG) 16 January 2014 See abstract, paragraphs [0042]-[0045] and figures 3,8.	1-42
A	US 2007-0047600 A1 (NINGYI LUO et al.) 01 March 2007 See abstract, paragraphs [0039]-[0043] and figures 1A,1B.	1-42
A	US 2014-0050234 A1 (VALERI V. TER-MIKIRTYCHEV) 20 February 2014 See abstract, paragraphs [0065]-[0068] and figure 4.	1-42

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
13 July 2015 (13.07.2015)

Date of mailing of the international search report
14 July 2015 (14.07.2015)

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
Republic of Korea
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