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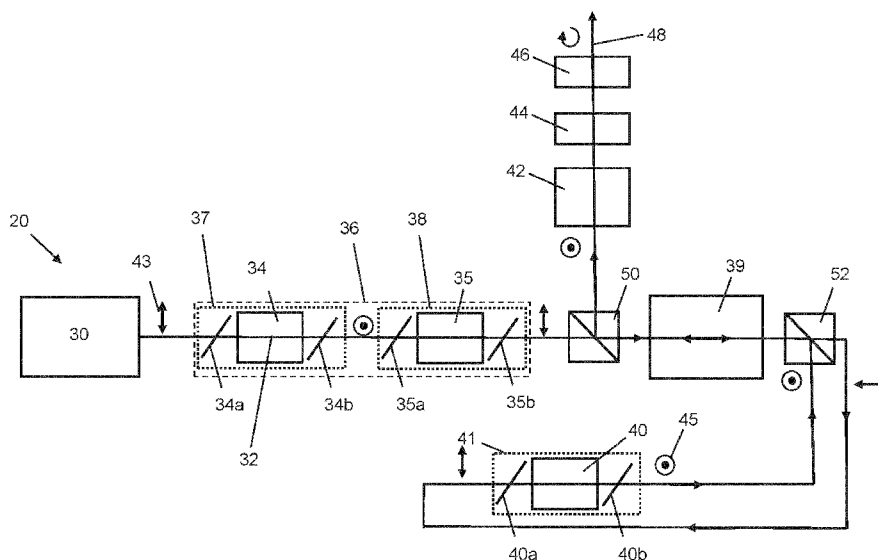


FIG. 3

(57) Abstract: A seed laser system for an EUV radiation source, the seed laser system comprising a laser configured to emit a pulsed laser beam, at least one electro-optic modulator located downstream of the laser, and an optical amplifier located downstream of the at least one electro-optic modulator, wherein the seed laser system further comprises an additional electro-optic modulator located downstream of the optical amplifier.

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SEED LASER SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 23177360.7 which was filed on 05 June 2023
5 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to a seed laser system. The seed laser system may form part
of a laser system, which may in turn form part of a laser produced plasma (LPP) radiation source. The
10 LPP radiation source may produce extreme ultraviolet (EUV) radiation and may form part of a
lithographic system.

BACKGROUND

[0003] A lithographic apparatus is a machine constructed to apply a desired pattern onto a
15 substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits
(ICs). A lithographic apparatus may, for example, project a pattern of a patterning device (e.g., a mask)
onto a layer of radiation-sensitive material (resist) provided on a substrate.

[0004] To project a pattern on a substrate a lithographic apparatus may use electromagnetic
radiation. The wavelength of this radiation determines the minimum size of features which can be
20 formed on the substrate. A lithographic apparatus, which uses extreme ultraviolet (EUV) radiation,
having a wavelength within the range 4-20 nm, for example 6.7 nm or 13.5 nm, may be used to form
smaller features on a substrate than a lithographic apparatus which uses, for example, radiation with a
wavelength of 193 nm.

[0005] EUV radiation for a lithographic apparatus may be produced by a laser produced plasma
25 (LPP) radiation source. Within an LPP radiation source, a laser beam may be used to irradiate fuel
droplets so as to produce a plasma which will emit EUV radiation.

[0006] It is desirable that the laser beam which is used to illuminate the fuel droplets has a high
power. A seed laser system may be used to provide a pulsed laser beam that is then amplified using
optical amplifiers. The optical amplifiers increase the power of the pulsed laser beam. The amplified
30 pulsed laser beam is incident upon fuel droplets, thereby generating EUV radiation.

[0007] A problem which may occur is that a small proportion of the amplified pulsed laser beam
may be reflected from a fuel droplet. The reflected radiation will be amplified by the optical amplifiers
and can cause damage to the seed laser.

[0008] It may be desirable to provide a seed laser which overcomes this problem, or another
35 problem associated with the prior art, in a manner which is not disclosed or suggested by the prior art.

SUMMARY

[0009] According to a first aspect of the invention there is provided a seed laser system for an EUV radiation source, the seed laser system comprising a laser configured to emit a pulsed laser beam, at least one electro-optic modulator located downstream of the laser, and an optical amplifier located downstream of the at least one electro-optic modulator, wherein the seed laser system further comprises an additional electro-optic modulator located downstream of the optical amplifier.

[00010] Advantageously, the electro-optic modulator located downstream of the optical amplifier protects the seed laser from radiation which may be back-reflected from a fuel droplet of the EUV radiation source. Advantageously, the electro-optic modulator is able to provide this protection with a faster switching time than an acousto-optic modulator (acousto-optic modulators are conventionally used to provide protection from back-reflected radiation).

[00011] A beam path of the seed laser system may comprise a first pass of the pulsed laser beam through the optical amplifier and a second pass of the pulsed laser beam through the optical amplifier.

[00012] The additional electro-optic modulator may be positioned after the first pass of the pulsed laser beam through the optical amplifier and before the second pass of the pulsed laser beam through the optical amplifier.

[00013] The additional electro-optic modulator may be configured to rotate the polarization of the pulsed laser beam before the second pass of the pulsed laser beam through the optical amplifier, such that the polarization of the pulsed laser beam during the second pass through the optical amplifier is generally orthogonal to the polarization of the pulsed laser beam during the first pass through the optical amplifier.

[00014] A polarizing beam splitter may be configured to direct the pulsed laser beam to the additional electro-optic modulator after the first pass of the pulsed laser beam through the optical amplifier, and to direct the pulsed laser beam to the second pass through the optical amplifier after the pulsed laser beam has passed through the additional electro-optic modulator.

[00015] The additional electro-optic modulator may be positioned after the second pass of the pulsed laser beam through the optical amplifier.

[00016] An acousto-optic modulator and a polarization rotator may be located in the beam path, downstream of the first pass of the pulsed laser beam through the optical amplifier and upstream of the second pass of the pulsed laser beam through the optical amplifier.

[00017] A polarizing beam splitter may be configured to direct the pulsed laser beam to the acousto-optic modulator after the first pass of the pulsed laser beam through the optical amplifier, and to direct the pulsed laser beam to the second pass through the optical amplifier after the pulsed laser beam has passed through the acousto-optic modulator and the polarization rotator.

[00018] The at least one electro-optic modulator may be located downstream of the laser and upstream of the optical amplifier is a pair of electro-optic modulators.

[00019] According to a second aspect of the invention there is provided a laser system comprising the seed laser system of the first aspect, and further comprising a laser beam amplification system which comprises series of optical amplifiers located downstream of the seed laser system.

[00020] The laser beam amplification system may comprise four optical amplifiers.

5 [00021] According to a third aspect of the invention there is provided a laser produced plasma radiation source comprising a fuel emitter operable to provide a fuel target at a plasma formation region, and the laser system of the second aspect of the invention.

[00022] According to a fourth aspect of the invention there is provided a lithographic system comprising the laser produced plasma radiation source of the third aspect, and a lithographic apparatus.

10 [00023] According to a fifth aspect of the invention there is provided a method of providing a pulsed laser beam for an EUV radiation source, the method comprising emitting a pulsed laser beam from a laser, then passing the pulsed laser beam through at least one electro-optic modulator located downstream of the laser, then passing the pulsed laser beam through an optical amplifier, then passing the pulsed laser beam through an additional electro-optic modulator located downstream of the optical
15 amplifier.

[00024] Advantageously, the electro-optic modulator located downstream of the optical amplifier protects the seed laser from radiation which may be back-reflected from a fuel droplet of the EUV radiation source. Advantageously, the electro-optic modulator is able to provide this protection with a faster switching time than an acousto-optic modulator (acousto-optic modulators are conventionally
20 used to provide protection from back-reflected radiation).

[00025] The pulsed laser beam may then pass through the optical amplifier for a second time.

[00026] The method may further comprise passing the pulsed laser beam through a laser beam amplification system which comprises series of optical amplifiers.

[00027] According to a sixth aspect of the invention there is provided a method of generating EUV
25 radiation comprising receiving a pulsed laser beam output from the series of optical amplifiers and directing the pulsed laser beam at fuel targets at a plasma formation region.

[00028] Features of different aspects of the invention may be combined together.

BRIEF DESCRIPTION OF THE DRAWINGS

30 [00029] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 schematically depicts a lithographic system comprising a lithographic apparatus and a radiation source according to an embodiment of the invention;
- Figure 2 schematically depicts a laser system according to an embodiment of the invention;
- 35 - Figure 3 schematically depicts a seed laser system according to an embodiment of the invention;
and

- Figure 4 schematically depicts a seed laser system according to an alternative embodiment of the invention.

DETAILED DESCRIPTION

5 [00030] Figure 1 shows a lithographic system according to an embodiment of the disclosure. The lithographic system comprises a radiation source SO and a lithographic apparatus LA. The radiation source SO is configured to generate an EUV radiation beam B and to supply the EUV radiation beam B to the lithographic apparatus LA. The lithographic apparatus LA comprises an illumination system IL, a support structure MT configured to support a patterning device MA (e.g., a mask), a projection system PS and a substrate table WT configured to support a substrate W.

10 [00031] The illumination system IL is configured to condition the EUV radiation beam B before the EUV radiation beam B is incident upon the patterning device MA. Thereto, the illumination system IL may include a faceted field mirror device 10 and a faceted pupil mirror device 11. The faceted field mirror device 10 and faceted pupil mirror device 11 together provide the EUV radiation beam B with a desired cross-sectional shape and a desired intensity distribution. The illumination system IL may include other mirrors or devices in addition to, or instead of, the faceted field mirror device 10 and faceted pupil mirror device 11.

15 [00032] After being thus conditioned, the EUV radiation beam B interacts with the patterning device MA. As a result of this interaction, a patterned EUV radiation beam B' is generated. The projection system PS is configured to project the patterned EUV radiation beam B' onto the substrate W. For that purpose, the projection system PS may comprise a plurality of mirrors 13, 14 which are configured to project the patterned EUV radiation beam B' onto the substrate W held by the substrate table WT. The projection system PS may apply a reduction factor to the patterned EUV radiation beam B', thus forming an image with features that are smaller than corresponding features on the patterning device MA. For example, a reduction factor of 4 or 8 may be applied. Although the projection system PS is illustrated as having only two mirrors 13, 14 in Figure 1, the projection system PS may include a different number of mirrors (e.g., six or eight mirrors).

25 [00033] The substrate W may include previously formed patterns. Where this is the case, the lithographic apparatus LA aligns the image, formed by the patterned EUV radiation beam B', with a pattern previously formed on the substrate W.

30 [00034] A relative vacuum, i.e., a small amount of gas (e.g., hydrogen) at a pressure well below atmospheric pressure, may be provided in the radiation source SO, in the illumination system IL, and/or in the projection system PS.

35 [00035] The radiation source SO shown in Figure 1 is, for example, of a type which may be referred to as a laser produced plasma (LPP) source. A laser system 1, which may, for example, include a CO₂ laser, is arranged to deposit energy via a pulsed laser beam 2 into a fuel, such as tin (Sn) which is provided from, e.g., a fuel emitter 3. Although tin is referred to in the following description, any suitable

fuel may be used. The fuel may, for example, be in liquid form, and may, for example, be a metal or alloy. The fuel emitter 3 may comprise a nozzle configured to direct tin, e.g., in the form of droplets, along a trajectory towards a plasma formation region 4. The laser pulsed beam 2 is incident upon the tin at the plasma formation region 4. The deposition of laser energy into the tin creates a tin plasma 7 at the plasma formation region 4. Radiation, including EUV radiation, is emitted from the plasma 7 during de-excitation and recombination of electrons with ions of the plasma.

[00036] The pulsed laser beam 2 which is incident upon the tin at the plasma formation region 4 may be referred to as a main laser beam or main pulsed laser beam. Individual pulses of this pulsed laser beam 2 may be referred to as main pulses.

[00037] Before the main laser beam 2 is incident upon the tin at the plasma formation region 4, another pre-pulse laser beam may be incident on the tin. The pre-pulse laser beam may act to change a shape of the tin so as to increase the conversion efficiency when the main pulse is (subsequently) incident on the tin. One or more additional pulses may be used. The pre-pulse laser beam and the one or more additional pulses may for example be provided by different lasers. The pre-pulse laser beam and the one or more additional pulses may travel along a beam path or paths which is different to a beam path of the main laser beam.

[00038] The EUV radiation from the plasma is collected and focused by a collector 5. Collector 5 comprises, for example, a near-normal incidence radiation collector 5 (sometimes referred to more generally as a normal-incidence radiation collector). The collector 5 may have a multilayer mirror structure which is arranged to reflect EUV radiation (e.g., EUV radiation having a desired wavelength such as 13.5 nm). The collector 5 may have an ellipsoidal configuration, having two focal points. A first one of the focal points may be at the plasma formation region 4, and a second one of the focal points may be at an intermediate focus 6, as discussed below.

[00039] The laser system 1 may be spatially separated from the radiation source SO. Where this is the case, the main laser beam 2 may be passed from the laser system 1 to the radiation source SO with the aid of a beam delivery system (not shown) comprising, for example, suitable directing mirrors and/or a beam expander, and/or other optics. The laser system 1, the radiation source SO and the beam delivery system may together be considered to be a radiation system.

[00040] Radiation that is reflected by the collector 5 forms the EUV radiation beam B. The EUV radiation beam B is focused at intermediate focus 6 to form an image at the intermediate focus 6 of the plasma present at the plasma formation region 4. The image at the intermediate focus 6 acts as a virtual radiation source for the illumination system IL. The radiation source SO is arranged such that the intermediate focus 6 is located at or near to an opening 8 in an enclosing structure 9 of the radiation source SO.

[00041] A laser system 1 according to an embodiment of the disclosure comprises a seed laser system 20 and a laser beam amplification system 21, as schematically depicted in Figure 2. A beam

steering system 26 which may deliver the resulting main laser beam 2 to the plasma formation region 4 (see Figure 1) is also depicted.

[00042] The laser beam amplification system 21 comprises four optical amplifiers 22-25. The optical amplifiers 22-25 may alternatively be referred to as laser beam amplifiers or optical amplifiers.

5 The optical amplifiers 22-25 are provided in series such that a first optical amplifier 22 amplifies a laser beam output by the seed laser system 20, the second optical amplifier 23 provides further amplification to the laser beam output from the first optical amplifier 22, the third optical amplifier 24 provides further amplification to the amplified laser beam output from the second optical amplifier 23, and the fourth optical amplifier 25 provides further amplification to the laser beam output from the third optical
10 amplifier 24. Thus, four amplification stages are applied to the laser beam by the four optical amplifiers 22-25, the amplification stages being provided in series and each increasing the power of the laser beam. The laser beam output from the fourth and final optical amplifier 25 passes to a beam steering system 26. The beam steering system 26 steers the amplified laser beam to the plasma formation region 4 (see Figure 1), where the amplified laser beam is incident upon fuel droplets and thereby generates EUV
15 radiation. The amplified laser beam is a pulsed laser beam and may be referred to as a main pulse laser beam.

[00043] Although four optical amplifiers 22-25 are depicted in Figure 2, a different number of laser amplifiers may be provided. In general, a series of optical amplifiers may be used.

[00044] A seed laser system 20 according to an embodiment of the disclosure is schematically
20 depicted in Figure 3. The seed laser system 20 comprises a laser 30 configured to emit a pulsed laser beam 32. The seed laser system further comprises first and second electro-optic modulators 34,35 (which may be referred to as EOMs 34,35). A pair of crossed polarization selective filters 34a, b, 35a, b are provided either side of each EOM 34, 35. An EOM together with associated polarization selective filters may be referred to as an EOM module. An EOM module will only transmit radiation when the
25 EOM is energized (when the EOM is not energized the pair of cross polarization selective filters will block the radiation). The first and second EOM modules 37, 38 may together be referred to as an electro-optic modulator pair 36 (or EOM module pair 36).

[00045] The pulsed laser beam 32 provided by the seed laser 30 is linearly polarized. This is schematically depicted by a double headed arrow 43 as polarization in the plane of Figure 3 (although
30 in other embodiments the linear polarization may have a different orientation). The pulsed laser beam 32 has the same polarization after it leaves the EOM module pair 36, as depicted by another double headed arrow (not labelled).

[00046] The pulsed laser beam 32 is incident upon a first polarizing beam splitter 50. The first polarizing beam splitter 50 is transmissive for the polarization of the pulsed laser beam 32.

35 **[00047]** An optical amplifier 39 is located downstream of the EOM module pair 36 and the first polarizing beam splitter 50. The optical amplifier 39 amplifies the pulsed laser beam 32.

[00048] A second polarizing beam splitter 52 is located downstream of the optical amplifier 39. The second polarizing beam splitter 52 is transmissive for the polarization of the pulsed laser beam 32.

[00049] An additional electro-optic modulator 40 (EOM 40) is located downstream of the optical amplifier 39 (and downstream of the second polarizing beam splitter 52). A pair of crossed polarization selective filters 40a, b are provided either side of the additional EOM 40. The additional EOM 40 and associated polarization selective filters 40a, b may be referred to as the additional EOM module 41. The additional EOM module 41 rotates the polarization of the pulsed laser beam 32 to a linear polarization which in this embodiment is perpendicular to the plane of Figure 3. This polarization is schematically depicted by a circle and disk 45.

[00050] The pulsed laser beam 32 passes back to the second polarizing beam splitter 52. The second polarizing beam splitter 52 is now reflective for the pulsed laser beam 32 (because the beam's polarization has been rotated). The pulsed laser beam 32 is reflected by the polarizing beam splitter 52, and passes back through the optical amplifier 39. The pulsed laser beam 32 thus undergoes two passes through the optical amplifier 39. An amplified pulsed laser beam is output from the optical amplifier 39.

[00051] The amplified pulsed laser beam 32 is reflected by the first polarizing beam splitter 50 towards an acousto-optic modulator 42 after the second pass through the optical amplifier 39.

[00052] The pulsed laser beam 32 passes through the acousto-optic modulator (AOM) 42, a polarization selective filter 44 and a reflective phase retarder 46. The reflective phase retarder modifies the polarization of the pulsed laser beam 32 from linear polarization to circular polarization. In other embodiments a quarter wave plate may be used to modify the polarization. In general, a polarization modification apparatus which converts linear polarization to circular polarization may be used. The resulting circularly polarized pulsed laser beam 48 passes to the laser beam amplification system 21 (see Figure 2).

[00053] In the depicted embodiment, the each polarizing beam splitter 50, 52 is arranged such that the polarizing beam splitter is transmissive for the pulsed laser beam 32 when it is first incident upon the polarizing beam splitter, and is reflective for the pulsed laser beam 32 when it is subsequently incident upon the polarizing beam splitter (the polarization of the pulsed laser beam has been rotated). In other embodiments, either or both of the polarizing beam splitters 50, 52 may be reflective for the pulsed laser beam 32 when it is first incident upon the polarizing beam splitter. This may apply for a polarizing beam splitter in any location in any embodiment of the invention.

[00054] In seed pulse conventional laser systems, the seed laser is used to provide the main pulse for EUV radiation generation and also a pedestal which precedes the main pulse. This pedestal is a low power portion of the pulse which may for example extend from the main pulse and precede the main pulse by around 250ns. The pedestal modifies the fuel droplet such that the main pulse is better absorbed by the fuel droplet. However, in a development of the laser system 1, the pedestal is replaced by a separately generated pulse. This separately generated pulse may be referred to as a fuel

modification pulse. The fuel modification pulse may have a different wavelength from the main pulse. The fuel modification pulse may for example have a wavelength of around 1 μm .

[00055] The EOM module pair 36 is configured to shorten pulses of the pulsed laser beam 32 emitted by the seed laser 30. The seed laser 30 may for example emit pulses having a duration of around 300ns. It may be desirable to provide main pulses of around 50ns. The EOM module pair 36 may be configured to reduce the duration of the pulses to around 50ns. Each EOM 34, 35 may be energized (switched on) for a period of 50ns (in this example) whilst a pulse of radiation is passing through that EOM. Each EOM module 37, 38 blocks radiation which falls outside of the 50ns period, thereby shortening the pulse. Other durations of pulse may be obtained using the EOM pair 36.

[00056] The pedestal provided by a conventional seed pulse laser system occurs because the EOM module pair 36 of a conventional system is not 100% effective. Specifically, each EOM 34, 35 and associated crossed polarization selective filters 34a, b, 35a, b is not 100% effective at blocking radiation when the EOM is not energized. The first EOM module 37 may for example suppress radiation outside of the switched on period by around 99%. Thus, a radiation pulse after the first EOM module 37 may comprise a pulse of around 50ns and an associated 300ns pedestal of lower power which precedes the pulse or is either side of the pulse. The second EOM module 38 and associated polarizer may for example suppress this pedestal by a further 99%. The EOM pair therefore suppress the pedestal by 99.99%. However, a significant pedestal may remain. In a conventional seed laser system, the pedestal is desirable because it modifies the fuel in a beneficial way. However, as noted above, in a development of the laser system the fuel modification may be provided by a separate pulse. As a result, the pedestal on the main pulse is not desirable. Instead, a shorted main pulse without a pedestal is desirable.

[00057] Since the EOM module pair 36 suppresses the pedestal incompletely, a straightforward course of action would be to add an extra EOM module immediately after the EOM module pair. However, the inventors have devised an alternative and advantageous way of suppressing the pedestal.

[00058] The additional EOM 40 is provided downstream of the first pass of the optical amplifier 39, and not immediately after the EOM pair 36. The three EOMs 34, 35, 40 in series (along with associated cross polarizers) suppresses a pedestal of the pulsed laser beam 32 such that the pedestal has a negligible power after the additional EOM 40. Because the pedestal has negligible power, it may also have negligible power after it has passed through the laser beam amplification system 21 (see Figure 1). In addition, the additional EOM 40 also rotates the polarization of the pulsed laser beam 32. This is advantageous because, as explained above, polarizing beam splitters 50, 52 are used to provide the second pass through the optical amplifier 39 and then direct the pulsed laser beam to an output of the seed laser system 20. Because the additional EOM 40 provides the required polarization rotation, this means that a separate polarization rotation apparatus is not required. This simplifies the configuration of the seed laser system 20.

[00059] As noted above, the pulsed laser beam 32 provided by the seed laser 30 is linearly polarized. This is schematically depicted by the double headed arrow 43 as polarization in the plane of

Figure 3 (although in other embodiments the linear polarization may have a different orientation). When the first EOM 34 is energized, it rotates the polarization of the pulsed laser beam 32 by 90°. Thus, after the first EOM 34 the polarization is perpendicular to the plane of Figure 3. This is schematically depicted by a circle and disk. When the second EOM 35 is energized, it rotates the polarization of the pulsed laser beam 32 by an additional 90°. The polarization rotation applied by the second EOM 35 may alternatively reverse the polarization rotation applied by the first EOM 34. Irrespective of the direction of rotation applied by the second EOM 35, the pulsed laser beam 32 when it leaves the EOM module pair 36 has the same linear polarization as when it entered the EOM pair (as depicted by the double-headed arrow). When the EOMs 34, 35 are not energized, the crossed polarizing filters 34a, b, 35a, b block the pulsed laser beam 32. Blocked radiation is directed to beam dumps (not depicted).

[00060] The pulsed laser beam 32 has polarization in the plane of Figure 3 when it undergoes the first pass through the optical amplifier 39. The pulsed laser beam 32 has polarization in the plane of Figure 3 when it enters the additional EOM module 41. When the additional EOM 40 of the additional EOM module 41 is energized, it rotates the polarization of the pulsed laser beam 32 by 90°. The rotated polarization is depicted by a circle and disk. When the additional EOM 40 is not energized, the crossed polarizing filters 40a, b block the pulsed laser beam 32. Blocked radiation is directed to beam dumps (not depicted).

[00061] Since the pulsed laser beam 32 now has a polarization which is perpendicular to the polarization during the first pass through the optical amplifier 39, the pulsed laser beam can now be directed to a second pass through the optical amplifier using the second polarizing beam splitter 52. The first polarizing beam splitter 50 can then direct the pulsed laser beam 32 to the acousto-optic modulator (AOM) 42.

[00062] The pulsed laser beam 32 passes through the acousto-optic modulator (AOM) 42. The AOM 42 directs the pulsed laser beam 32 towards the polarization selective filter 44 when it is energized and directs the pulsed laser beam towards a beam dump (not depicted) when it is not energized. The polarization selective filter 44 transmits radiation which is polarized perpendicular to the plane of Figure 3. The pulsed laser beam 32 is polarized perpendicular to the plane of Figure 3 and thus is transmitted by the polarization selective filter 44. The quarter-wave plate 46 applies circular polarization to the pulsed laser beam 32. The resulting circularly polarized amplified pulsed laser beam 48 then passes to the laser amplification system 21 (see Figure 2).

[00063] As noted above, the additional EOM 40 advantageously contributes to removal of a pedestal from pulses of the pulsed laser beam 32, and in addition provides polarization rotation to facilitate the second pass of the pulsed laser beam through the optical amplifier 39. The second pass of the pulsed laser beam 32 through the optical amplifier 39 is desirable because this provides more effective amplification of the pulsed laser beam than would be provided by a single pass. In other

words, more efficient gain extraction from the gain medium is obtained (compared with a single pass). The gain medium may for example be CO₂ gas.

[00064] As noted above, the polarization rotation provided by the additional EOM 40 advantageously avoids the need for an additional polarization rotation apparatus (e.g., half wave plate).

5 An advantage of using the EOM 40 instead of an AOM is that the EOM does not require focusing of the pulsed laser beam into the EOM. Focusing of the pulsed laser beam into an AOM may be needed in order to achieve a desired switching speed. Such focusing can give rise to undesirable thermal lensing or other undesirable effects. These advantages are provided because the additional EOM 40 is downstream of the first pass of the optical amplifier 39 and would not be achieved if the additional
10 EOM were to be located immediately after the EOM pair 36.

[00065] The additional EOM 40 is located downstream of the first pass of the optical amplifier 39. This goes against the understanding of the skilled person that an EOM should not be located downstream of an optical amplifier for a pulsed laser beam 32 because the power of the pulsed laser beam will damage the EOM. The power level of the pulsed laser beam 32 when it passes through the
15 additional EOM 40 may for example be around 50W. Providing the additional EOM 40 at a location where it will experience power levels of around 50W and is able to operate reliably for an extended period of time (e.g., years) goes against the general understanding of those skilled in the art. It is particularly important that a lithographic apparatus is able to operate reliably for an extended period of time, because interruption of the operation of the lithographic apparatus is very expensive due to lost
20 production when operation ceases. The additional EOM 40 is able to provide reliable operation for an extended period of time contrary to the general understanding of those skilled in the art. The general understanding of those skilled in the art is that there is a risk that an EOM which experiences power levels of around 50W may become damaged. For this reason, the general understanding of those skilled in the art is that where a modulator is required to handle powers of around 50W then an acousto-optic
25 modulator must be used (it being understood that acousto-optic modulators are less liable to be damaged by higher optical powers). Contrary to the general understanding of those skilled in the art, the inventors have found that the additional EOM 40 can handle powers of around 50W or more without being damaged.

[00066] As noted further above, some radiation may be back-reflected from a fuel droplet. This
30 back-reflected radiation may pass through the laser beam amplification system 21, and thus may be amplified. The back-reflected laser beam could damage the seed laser 30. As explained above, the amplified pulsed laser beam 48 is circularly polarized. Radiation which is reflected from a fuel droplet has the opposite circular polarization. This means that after passing through the quarter-wave plate 46, the reflected radiation has linear polarization which is opposite to the pulsed laser beam 32 (i.e., in the
35 plane of Figure 3). The polarization selective filter 44 only transmits radiation with polarization out of the plane of Figure 3, and thus blocks the back-reflected radiation. However, a small proportion of the radiation (e.g., around 5%) passes through the polarization selective filter 44. This may be because for

example a small component of the back-reflected radiation has a polarization out of the plane of Figure 3.

[00067] The AOM 42 is de-energized when the small proportion of the back-reflected radiation is incident at the AOM, and thus blocks the back-reflected radiation. However, operation of the AOM 42 is relatively slow, and as a result a small proportion of the back-reflected radiation may be transmitted by the AOM (the AOM may be not fully de-energized). Back reflected radiation which passes through the AOM 42 passes through the optical amplifier 39 and will be amplified by the optical amplifier. The additional EOM module 41 blocks this amplified back-reflected radiation. The additional EOM module 41 includes crossed polarizers 40a, b and will only transmit radiation when the EOM is energized, because polarization rotation is needed in order for radiation transmission to occur. The additional EOM 40 is not energized when the back-reflected radiation is incident at the additional EOM (operation of EOMs is much faster than operation of AOMs). Thus, the additional EOM 40 blocks the back-reflected radiation. The back-reflected radiation thus does not undergo a second pass through the optical amplifier 39 and does not travel back to the seed laser 30.

[00068] The additional EOM 40 after the first pass of the optical amplifier 39 has a further advantage compared with the situation if an AOM were to be provided instead of the additional EOM. This arises from the fast-switching speed of the additional EOM compared with an AOM. If an AOM were to be provided instead of the additional EOM then, in order to accommodate the slow switching speed of the AOM, the pulsed laser beam 32 would need to be focused within the AOM (the switching speed is limited by the time taken for an acoustically generated grating to pass through the pulsed laser beam). This focusing of the pulsed laser beam, which may cause damage to optical components, is not needed for the additional EOM 40 because the additional EOM provides faster switching than an AOM. Thus, potential damage to optical components due to focusing is avoided.

[00069] The additional EOM 40 prevents radiation from passing twice through the optical amplifier 39 when it is not energized. This may prevent self-lasing in the seed laser system 20. The AOM 42 prevents radiation from passing through the laser beam amplification system 21 and then through the optical amplifier 39 when it is not energized. Again, this may prevent self-lasing.

[00070] Figure 4 schematically depicts a seed laser system 20 according to an alternative embodiment of the invention. In common with the embodiment depicted in Figure 3, the seed laser system 20 comprises a seed laser 30 configured to emit a pulsed laser beam 32, an EOM pair 36, and an optical amplifier 39. Features of the embodiment of Figure 4 which correspond with features of the embodiment of Figure 3 are provided with the same reference numerals, and in some instances are not described again.

[00071] In this embodiment, an acousto-optic modulator (AOM) 60 is located downstream of the first pass of the optical amplifier 39. A polarization rotator 62 is located downstream of the AOM 60. The polarization rotator 62 may for example be a half-wave plate, and is configured to rotate the polarization of the pulsed laser beam 32 by 90°.

[00072] An additional EOM 64 is located after the second pass of the optical amplifier 39. Crossed polarizers 64a, b are provided either side of the additional EOM. The crossed polarizer pair 64a, b and the additional EOM 64 may be referred to as an additional EOM module 66.

[00073] A polarization selective filter 44 and a polarization modification apparatus 46 (e.g., reflective phase retarder 46 or quarter wave plate) are located downstream of the EOM module 66.

[00074] Operation of the embodiment of Figure 4 is similar to operation of the embodiment of Figure 3. That is, the pulsed laser beam 32 passes through the EOM module pair 36, which suppresses the pedestal. The pulsed laser beam 32 then undergoes a first pass through the optical amplifier 39. After this, the pulsed laser beam 32 is transmitted by the AOM (which is transmitting when a pulse of radiation arrives but is blocking at other times). The polarization of the pulsed laser beam 32 is then rotated by the polarization rotator 62. The second polarizing beam splitter 52 directs the pulsed laser beam 32 through a second pass through the optical amplifier 39. The pulsed laser beam 32 is then reflected by the first polarizing beam splitter 50 to the additional EOM 64. The polarization of the pulsed laser beam 32 is rotated by the additional EOM 64. The pulsed laser beam 32 passes through the polarization selective filter 44 and is changed to circular polarization by the quarter-wave plate 46. The circularly polarized amplified pulsed laser beam 48 is then output to the laser beam amplification system 21 (see Figure 2).

[00075] The additional EOM 64 provides similar functionality to the additional EOM 40 of the embodiment depicted in Figure 3. That is, the additional EOM 64 removes a residual pedestal from pulses of the pulsed laser beam 32 such that the pedestal is negligible. The additional EOM 64 is more effective at preventing back-reflected radiation from reaching the optical amplifier 39 than the AOM of the embodiment of Figure 3. Thus, depletion of gain from the optical amplifier 39 which could occur in the embodiment of Figure 3 may be prevented by the embodiment of Figure 4. A disadvantage of the embodiment of Figure 4 is that the additional EOM 64 experiences higher optical power than the additional EOM of the embodiment of Figure 3.

[00076] The power level experienced by the additional EOM 64 may for example be around 200W or more. Providing the additional EOM 64 at a location where it will experience these power levels goes against the conventional understanding of those skilled in the art, for the reasons explained further above. Contrary to the general understanding of those skilled in the art, the inventors have found that it is possible for the additional EOM 64 to handle powers of around 200W or more without being damaged.

[00077] The AOM 60 prevents radiation from passing twice through the optical amplifier 39 when it is not energized. This may prevent self-lasing in the seed laser system 20. The additional EOM 64 prevents radiation from passing through the laser beam amplification system 21 and then through the optical amplifier 39 when it is not energized. Again, this may prevent self-lasing.

[00078] The specific polarizations of the pulsed laser beam 32 in the depicted embodiments are merely examples. Other linear polarizations may be used.

[00079] The laser beam pulse duration of 300ns emitted by the seed laser 30 is merely an example. The seed laser 30 may emit a laser beam with pulses of a different duration, e.g., of the order of 100s of ns.

[00080] The seed laser 30 may emit a laser beam with a wavelength of around 10 μ m. The seed laser 30 may emit a laser beam with a different wavelength, e.g., around 1 μ m.

[00081] The laser beam pulse duration of 50ns after shortening by the EOMs is merely an example. The pulses may have a different duration, e.g., of the order of 10s of ns.

[00082] The polarizing beam splitters 50 52 may be polarizing beam splitting cubes. Other polarization-selective beam-splitters may be used. In general, any suitable polarization selective elements may be used.

[00083] Although depicted embodiments of the invention comprise an EOM pair before the optical amplifier 39, in other embodiments a different number of EOMs may be provided before the optical amplifier. A single EOM may be provided before the optical amplifier.

[00084] Embodiments of the invention may be particularly advantageous when it is desired to remove a pedestal from a pulses of a pulsed laser beam. However, embodiments of the invention may be used when it is desired to retain a pedestal on pulses of the pulsed laser beam. For example, in an embodiment a single EOM may be provided instead of the EOM pair.

[00085] Although specific reference may be made in this text to the use of lithographic apparatus in the manufacture of ICs, it should be understood that the lithographic apparatus described herein may have other applications. Possible other applications include the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, flat-panel displays, liquid-crystal displays (LCDs), thin-film magnetic heads, etc.

[00086] Although specific reference may be made in this text to embodiments of the invention in the context of a lithographic apparatus, embodiments of the invention may be used in other apparatus.

Embodiments of the invention may form part of a mask inspection apparatus, a metrology apparatus, or any apparatus that measures or processes an object such as a wafer (or other substrate) or mask (or other patterning device). These apparatuses may be generally referred to as lithographic tools. Such a lithographic tool may use vacuum conditions or ambient (non-vacuum) conditions.

[00087] While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The descriptions above are intended to be illustrative, not limiting. Thus, it will be apparent to one skilled in the art that modifications may be made to the invention as described without departing from the scope of the claims set out below.

[00088] Clauses

1. A seed laser system for an EUV radiation source, the seed laser system comprising a laser configured to emit a pulsed laser beam, at least one electro-optic modulator located downstream of the laser, and an optical amplifier located downstream of the at least one electro-optic modulator, wherein

the seed laser system further comprises an additional electro-optic modulator located downstream of the optical amplifier.

2. The seed laser system of clause 1, wherein a beam path of the seed laser system comprises a first pass of the pulsed laser beam through the optical amplifier and a second pass of the pulsed laser beam through the optical amplifier.

3. The seed laser system of clause 2, wherein the additional electro-optic modulator is positioned after the first pass of the pulsed laser beam through the optical amplifier and before the second pass of the pulsed laser beam through the optical amplifier.

4. The seed laser system of clause 3, wherein the additional electro-optic modulator is configured to rotate the polarization of the pulsed laser beam before the second pass of the pulsed laser beam through the optical amplifier, such that the polarization of the pulsed laser beam during the second pass through the optical amplifier is generally orthogonal to the polarization of the pulsed laser beam during the first pass through the optical amplifier.

5. The seed laser system of clause 4, wherein a polarizing beam splitter is configured to direct the pulsed laser beam to the additional electro-optic modulator after the first pass of the pulsed laser beam through the optical amplifier, and to direct the pulsed laser beam to the second pass through the optical amplifier after the pulsed laser beam has passed through the additional electro-optic modulator.

6. The seed laser system of clause 2, wherein the additional electro-optic modulator is positioned after the second pass of the pulsed laser beam through the optical amplifier.

7. The seed laser system of clause 6, wherein an acousto-optic modulator and a polarization rotator are located in the beam path downstream of the first pass of the pulsed laser beam through the optical amplifier and upstream of the second pass of the pulsed laser beam through the optical amplifier.

8. The seed laser system of clause 7, wherein a polarizing beam splitter is configured to direct the pulsed laser beam to the acousto-optic modulator after the first pass of the pulsed laser beam through the optical amplifier, and to direct the pulsed laser beam to the second pass through the optical amplifier after the pulsed laser beam has passed through the acousto-optic modulator and the polarization rotator.

9. The seed laser system of any preceding clause, wherein the at least one electro-optic modulator located downstream of the laser and upstream of the optical amplifier is a pair of electro-optic modulators.

10. A laser system comprising the seed laser system of any preceding clause, and further comprising a laser beam amplification system which comprises series of optical amplifiers located downstream of the seed laser system.

11. The laser system of clause 10, wherein the laser beam amplification system comprises four optical amplifiers.

12. A laser produced plasma radiation source comprising:
a fuel emitter operable to provide a fuel target at a plasma formation region; and
the laser system of clause 10 or clause 11.

13. A lithographic system comprising:
the laser produced plasma radiation source of clause 12; and
a lithographic apparatus.
14. A method of providing a pulsed laser beam for an EUV radiation source, the method comprising
5 emitting a pulsed laser beam from a laser, then passing the pulsed laser beam through at least one
electro-optic modulator located downstream of the laser, then passing the pulsed laser beam through an
optical amplifier, then passing the pulsed laser beam through an additional electro-optic modulator
located downstream of the optical amplifier.
15. The method of clause 14, wherein the pulsed laser beam then passes through the optical
10 amplifier for a second time.
16. The method of clause 14 or clause 15, further comprising passing the pulsed laser beam through
a laser beam amplification system which comprises series of optical amplifiers.
17. A method of generating EUV radiation comprising receiving a pulsed laser beam output from
the series of optical amplifiers of clause 16, and directing the pulsed laser beam at fuel targets at a
15 plasma formation region.

CLAIMS

1. A seed laser system for an EUV radiation source, the seed laser system comprising a laser configured to emit a pulsed laser beam, at least one electro-optic modulator located downstream of the laser, and an optical amplifier located downstream of the at least one electro-optic modulator, wherein the seed laser system further comprises an additional electro-optic modulator located downstream of the optical amplifier.
2. The seed laser system of claim 1, wherein a beam path of the seed laser system comprises a first pass of the pulsed laser beam through the optical amplifier and a second pass of the pulsed laser beam through the optical amplifier.
3. The seed laser system of claim 2, wherein the additional electro-optic modulator is positioned after the first pass of the pulsed laser beam through the optical amplifier and before the second pass of the pulsed laser beam through the optical amplifier.
4. The seed laser system of claim 3, wherein the additional electro-optic modulator is configured to rotate the polarization of the pulsed laser beam before the second pass of the pulsed laser beam through the optical amplifier, such that the polarization of the pulsed laser beam during the second pass through the optical amplifier is generally orthogonal to the polarization of the pulsed laser beam during the first pass through the optical amplifier.
5. The seed laser system of claim 4, wherein a polarizing beam splitter is configured to direct the pulsed laser beam to the additional electro-optic modulator after the first pass of the pulsed laser beam through the optical amplifier, and to direct the pulsed laser beam to the second pass through the optical amplifier after the pulsed laser beam has passed through the additional electro-optic modulator.
6. The seed laser system of claim 2, wherein the additional electro-optic modulator is positioned after the second pass of the pulsed laser beam through the optical amplifier.
7. The seed laser system of claim 6, wherein an acousto-optic modulator and a polarization rotator are located in the beam path downstream of the first pass of the pulsed laser beam through the optical amplifier and upstream of the second pass of the pulsed laser beam through the optical amplifier.
8. The seed laser system of claim 7, wherein a polarizing beam splitter is configured to direct the pulsed laser beam to the acousto-optic modulator after the first pass of the pulsed laser beam through

the optical amplifier, and to direct the pulsed laser beam to the second pass through the optical amplifier after the pulsed laser beam has passed through the acousto-optic modulator and the polarization rotator.

9. The seed laser system of any preceding claim, wherein the at least one electro-optic modulator located downstream of the laser and upstream of the optical amplifier is a pair of electro-optic modulators.

10. A laser system comprising the seed laser system of any preceding claim, and further comprising a laser beam amplification system which comprises series of optical amplifiers located downstream of the seed laser system.

11. A laser produced plasma radiation source comprising:
a fuel emitter operable to provide a fuel target at a plasma formation region; and
the laser system of claim 10.

12. A lithographic system comprising:
the laser produced plasma radiation source of claim 11; and
a lithographic apparatus.

13. A method of providing a pulsed laser beam for an EUV radiation source, the method comprising emitting a pulsed laser beam from a laser, then passing the pulsed laser beam through at least one electro-optic modulator located downstream of the laser, then passing the pulsed laser beam through an optical amplifier, then passing the pulsed laser beam through an additional electro-optic modulator located downstream of the optical amplifier.

14. The method of claim 13, wherein the pulsed laser beam then passes through the optical amplifier for a second time, the method further comprising passing the pulsed laser beam through a laser beam amplification system which comprises series of optical amplifiers.

15. A method of generating EUV radiation comprising receiving a pulsed laser beam output from the series of optical amplifiers of claim 14, and directing the pulsed laser beam at fuel targets at a plasma formation region.

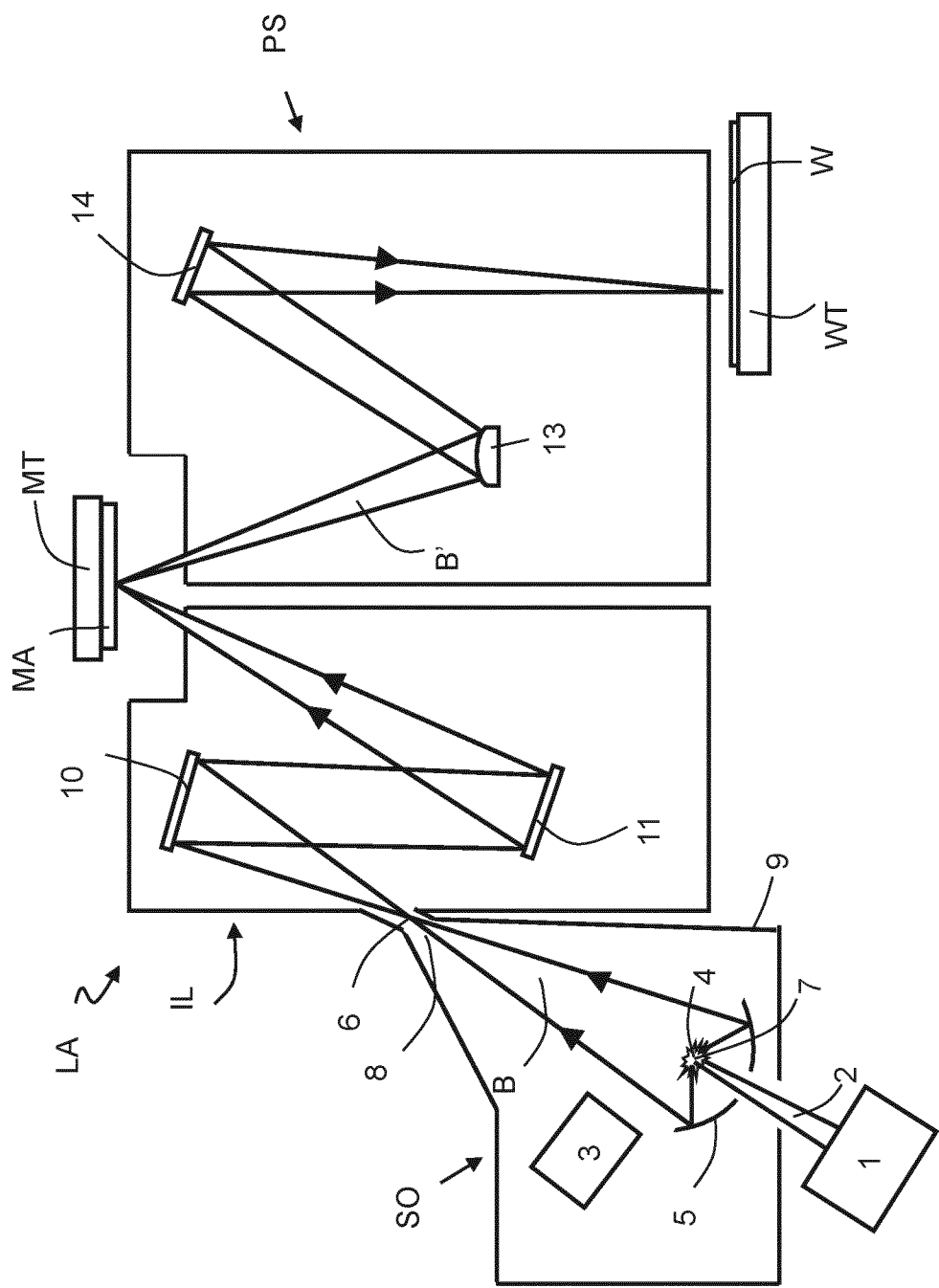


FIG. 1

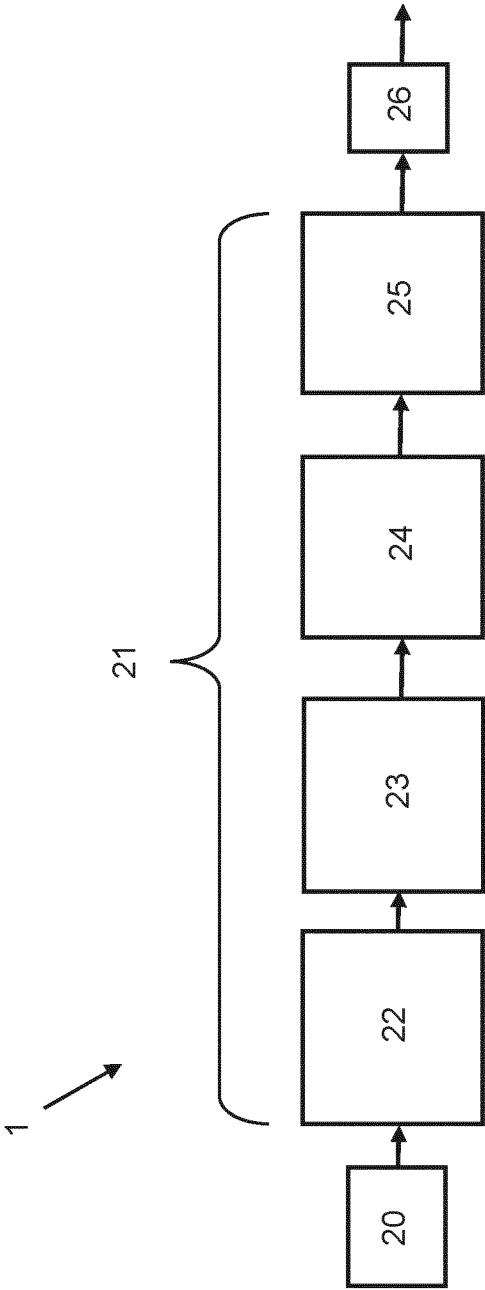


FIG. 2

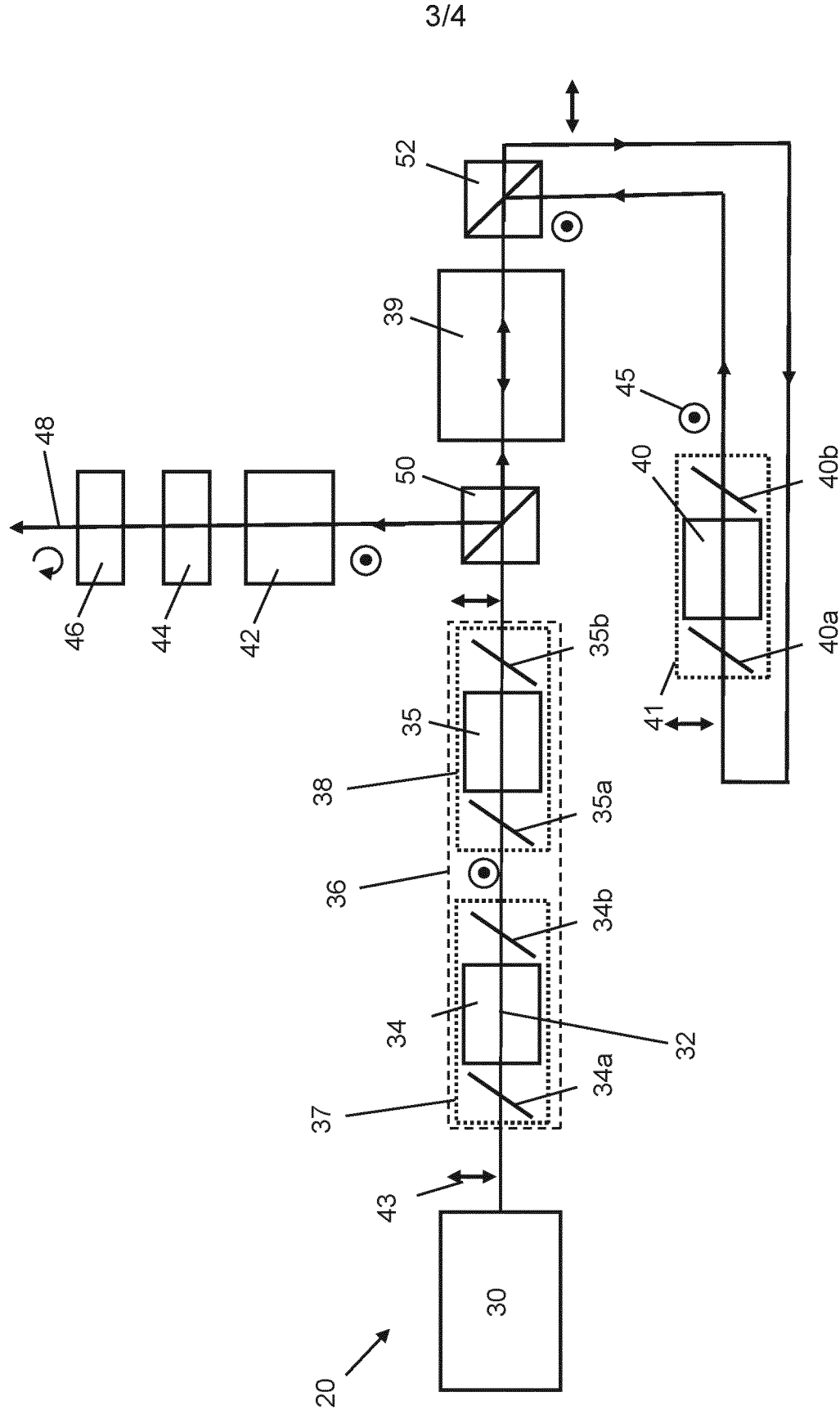


FIG. 3

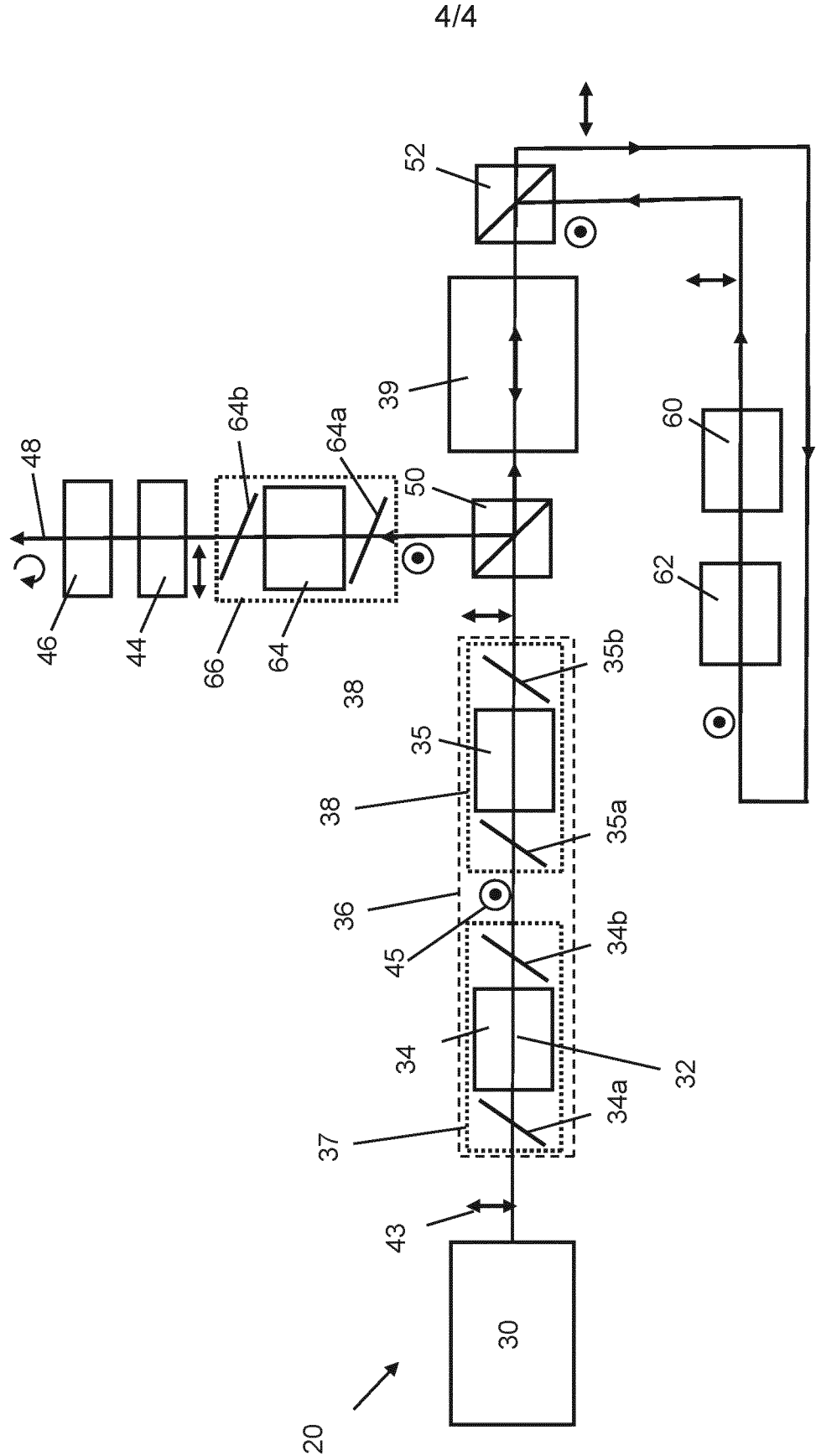


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/063367

A. CLASSIFICATION OF SUBJECT MATTER					
INV.	H01S3/00	H01S3/10	H01S3/107	H01S3/23	H01S3/223
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					
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	US 2013/032735 A1 (NOWAK KRZYSZTOF [JP] ET AL) 7 February 2013 (2013-02-07) paragraph [0100] - paragraph [0103]; figure 1 paragraph [0112] - paragraph [0114]; figure 3 paragraph [0119] - paragraph [0124]; figure 7 paragraph [0226]; figure 39 paragraph [0230] - paragraph [0234]; figure 43 ----- - / - -				1 - 5, 10 - 15
☒ Further documents are listed in the continuation of Box C.					
☒ See patent family annex.					
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Date of the actual completion of the international search			Date of mailing of the international search report		
2 August 2024			12/08/2024		
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016			Authorized officer Hervé, Denis		

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International application No

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