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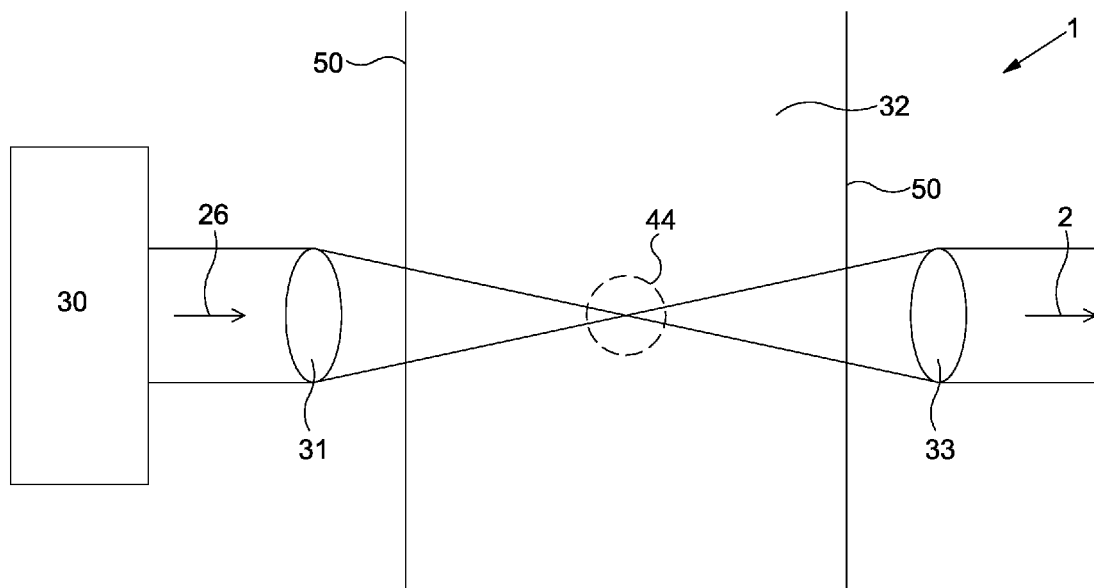


Fig. 2

(57) Abstract: An EUV radiation source of a laser-produced-plasma type, comprising: a fuel emitter configured to produce fuel droplets; and a laser system configured to illuminate a fuel droplet with radiation for converting the fuel droplet into a plasma at a plasma formation region; wherein the laser system comprises: a laser configured to produce radiation of a first wavelength; and a nonlinear medium configured to receive radiation of the first wavelength, produce radiation of a second wavelength using a nonlinear optical process at a radiation conversion region, and deliver radiation of the second wavelength to the plasma formation region; wherein the second wavelength is longer than the first wavelength.



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EUV radiation source and related methods**CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims priority of EP application 19151860.4, which was filed on 15 January 2019 and EP application 19164608.2, which was filed on 22 March 2019. Both applications are incorporated herein in their entirety by reference.

FIELD

[0002] The present invention relates to an extreme ultraviolet radiation source of a laser-produced plasma type, and related methods. The extreme ultraviolet radiation source may form part of a lithographic system.

BACKGROUND

[0003] A lithographic apparatus is a machine constructed to apply a desired pattern onto a 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 at 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 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 conventional lithographic apparatus (which may use, for example, radiation with a wavelength of 193 nm).

[0005] One known type of EUV radiation source directs laser radiation onto fuel droplets. This converts the fuel droplets into EUV radiation emitting plasma. A radiation source of this type may be referred to as a laser-produced plasma (LPP) source. Known LPP sources suffer from poor conversion efficiency. That is, the power of EUV radiation which they output is a small fraction of the power of laser radiation which is incident upon the fuel droplets.

[0006] It may be desirable to provide an EUV radiation source which has a better efficiency than a conventional LPP radiation source, or which overcomes some other disadvantage associated with conventional LPP radiation sources.

SUMMARY

[0007] According to a first aspect of the present invention, there is provided an EUV radiation source of laser-produced plasma (LPP) type, comprising a fuel emitter configured to produce fuel droplets; and a laser system configured to illuminate a fuel droplet with radiation for converting the fuel droplet into a plasma at a plasma formation region; wherein the laser system comprises: a laser

configured to produce radiation of a first wavelength; and a nonlinear medium configured to receive radiation of the first wavelength, produce radiation of a second wavelength using a nonlinear optical process at a radiation conversion region, and deliver radiation of the second wavelength to the plasma formation region; wherein the second wavelength is longer than the first wavelength.

5 [0008] Conventional LPP radiation sources have a low conversion efficiency. The conversion efficiency is, in part, dependent on the wavelength of the laser radiation used to illuminate fuel droplets. The production of radiation of a second wavelength allows a different wavelength to be used to illuminate the fuel droplet compared to conventional sources. The second wavelength may be chosen to improve the conversion efficiency of the EUV radiation source.

10 [0009] The second wavelength may have additional benefits. For example, radiation from conventional laser sources may reflect off fuel droplets. The reflected radiation may cause damage to the laser system and other apparatus. The second wavelength may be chosen to minimize reflection from the fuel droplets. A reduced reflection is advantageous to reduce the risk of damage. A reduced reflection is also advantageous because it reduces the amount of optical power lost to reflections,
15 further increasing the conversion efficiency of the EUV radiation source.

[0010] The laser associated with the laser system may comprise a YAG-based laser, for example a Nd:YAG or Yb:YAG laser. YAG-based lasers are advantageous over conventional lasers, for example CO₂ lasers, because they have a high wall-plug efficiency, around 5x higher than CO₂ lasers. That is, when powered with electric power, they convert a larger proportion of electrical power to
20 optical power. YAG-based lasers are also advantageous because they have a smaller footprint than conventional lasers, for example CO₂ lasers. That is, they take up less floor space than other conventional laser systems which may be beneficial for space and/or transport and/or cost. YAG-based lasers are also beneficial because they can provide highly energetic pulses (in the range 0.1 – 10 J/pulse, for example above 1 J/pulse) at high repetition rates (in the range 10 – 100 kHz, for example
25 50 kHz). The YAG-based laser may emit radiation around 1.0 micron. For example, a Nd:YAG laser may emit around 1.06 micron, a Yb:YAG laser may emit around 1.03 micron. Alternatively, a holmium-doped YAG (Ho:YAG) laser may emit around 2.10 micron, and a thulium-doped YAG (Tm:YAG) laser may emit around 2.00 micron. However, Nd:YAG and Yb:YAG lasers may be advantageous as they provide higher power than Ho:YAG and Tm:YAG lasers.

30 [0011] The laser system may produce radiation with a second wavelength in the range 1.4 - 12 micron. For example, a Nd:YAG laser in combination with a gaseous methane nonlinear medium will produce radiation at about 1.54 micron. Alternatively, a Yb:YAG laser in combination with a gaseous methane nonlinear medium will produce radiation at about 1.47 micron. Alternatively, a Ho:YAG in combination with a gaseous methane nonlinear medium will produce radiation at about 5.41 micron.
35 Alternatively, a Tm:YAG laser in combination with a gaseous methane nonlinear medium will produce radiation at about 11.85 micron.

[00012] The laser system may produce radiation with a second wavelength in the range 1.4 – 2.4 micron.

[00013] The laser system may produce radiation with a second wavelength in the range 1.9 – 2.4 micron. For example, a Nd:YAG laser in combination with an optical parametric oscillator comprising a KTP crystal may produce radiation tuneable in the range 1.9 to 2.4 micron.

[00014] The laser system may produce radiation with a second wavelength in the range 1.4 – 2 micron. For example, a Yb:YAG laser in combination with a gaseous hydrogen nonlinear medium will produce radiation at about 1.80 micron. Alternatively, a Nd:YAG laser in combination with a gaseous hydrogen nonlinear medium will produce radiation at about 1.91 micron. The use of Nd:YAG or Yb:YAG lasers in these embodiments allows the production of an advantageous second wavelength at high powers.

[00015] In another embodiment, the laser system may produce radiation with a second wavelength about 1.91 micron. This wavelength is beneficial for improving conversion efficiency and can be provided at high powers.

[00016] The fuel droplets may be illuminated only by radiation of the second wavelength. Alternatively, both radiation at the first and second wavelengths may be used to illuminate fuel droplets. Using both radiation at the first and second wavelengths may be advantageous because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system unnecessarily.

[00017] The nonlinear medium may comprise a Raman-active material. The nonlinear optical process may be Stimulated Raman Scattering (SRS). SRS converts incident radiation of a first wavelength into radiation of a second, longer, wavelength. SRS enables the provision of radiation of a second, longer, wavelength.

[00018] The nonlinear medium may comprise a gas, for example hydrogen or methane. The gas may be pressurized at a pressure higher than atmospheric pressure, for example in the range 3 – 10 bar.

[00019] For EUV lithography, a high repetition rate of EUV pulses is advantageous because more energy can be imparted to the substrate in a shorter time, thereby allowing a higher throughput. It is beneficial therefore to provide an EUV radiation source that can sustain high repetition rates (in the range 10 – 100 kHz, for example 50 kHz). Pulsed laser light is conventionally used in LPP generation of EUV radiation. The high intensities associated with pulses of laser radiation in an EUV source may lead to ionization in the radiation conversion region.

[00020] In one embodiment of the present invention, a gas flow system is provided. The gas flow system may be configured to replace ionized gas in the radiation conversion region with non-ionized gas.

[00021] The gas flow system may comprise a gas flow pathway and a pump to circulate gas around the gas flow pathway. This circulation urges ionized gas away from the radiation conversion region and urges non-ionized gas into the radiation conversion region.

[00022] The laser system may further comprise an optical parametric oscillator (OPO). The OPO may comprise the nonlinear medium. The nonlinear medium may comprise a nonlinear crystal. For example, the nonlinear medium may comprise one of: potassium titanyl arsenate (KTA), potassium titanyl phosphate (KTP), barium borate (BBO) or lithium niobate (LN), periodically poled KTP (PPKTP), periodically poled LN (PPLN), rubidium doped KTP (RKTP), or periodically poled rubidium doped KTP (PPRKTP). The use of nonlinear crystals enables high power scalability as they can be efficiently cooled. As such, nonlinear crystals can be used to achieve conversion at high pulse repetition rates. The OPO may further comprise an optical cavity. The nonlinear optical process may be second-order nonlinear optical interaction. The OPO may convert input radiation of a first wavelength into output radiation of a second, longer, wavelength. The OPO enables the provision of radiation of a second, longer, wavelength. The output radiation wavelength may be tuneable. For example, a Nd:YAG laser in combination with an OPO comprising a KTP crystal may produce output radiation with a second wavelength tunable in the range 1.9 to 2.4 micron. Second wavelengths in the range 1.9 to 2.4 micron may be beneficial for the efficient production of EUV radiation via LPP.

[00023] The OPO may also produce radiation of a third wavelength at the radiation conversion region. The third wavelength may be the same wavelength as the second wavelength, for example using a Nd:YAG laser in combination with an OPO comprising a KTP crystal may be tuned to produce radiation of the second wavelength and third wavelength both about 2.1 micron. Alternatively, the second and third wavelengths may have different values.

[00024] The fuel droplets may also be illuminated by radiation of the third wavelength. Using radiation of the third wavelength in addition to radiation of the first and second wavelengths may be advantageous because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system unnecessarily.

[00025] The EUV radiation source may further comprise an optical parametric amplifier to amplify at least one of the radiation of the second wavelength or the radiation of the third wavelength. The optical parametric amplifier may be configured to amplify radiation of the second and/or third wavelength using pump radiation. The pump radiation may be provided by the laser configured to produce radiation of the first wavelength, i.e. the pump radiation may have the same wavelength as the first wavelength. The pump radiation may be provided by a separate source, i.e. the laser system may comprise a second laser. The pump radiation may have a fourth wavelength different to the first wavelength. The fuel droplets may also be illuminated by radiation of the fourth wavelength. Using radiation of the fourth wavelength in addition to radiation of the first and/or second and/or third wavelengths may be advantageous because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system unnecessarily.

[00026] The EUV radiation source may further comprise a delay stage after the radiation conversion region. The delay stage may be configured to delay the arrival of at least a portion of the radiation at the plasma formation region. Radiation of the first and/or second and/or third and/or fourth wavelength may be passed through the delay stage. The delay stage may be configured to increase the temporal pulse length of radiation arriving at the plasma formation region. For example, by delaying the arrival of radiation of the third wavelength with respect to radiation of the second wavelength, the temporal pulse length of radiation arriving at the plasma formation region may be increased. The temporal pulse length is a measure of the duration of a pulse of radiation. A longer temporal pulse length may be advantageous for EUV conversion efficiency at the plasma formation region.

[00027] Radiation of the first and/or second and/or third and/or fourth wavelength arriving at the plasma formation region may be used as a main pulse i.e. single pulse for EUV radiation formation. Alternatively, radiation of the first and/or second and/or third and/or fourth wavelength arriving at the plasma formation region may be used as a main pulse in combination with an additional pulse of radiation, for example a pre-pulse to deform the fuel droplet prior to arrival of the main pulse. The pre-pulse may optimally shape the fuel droplet for more efficient EUV generation.

[00028] In a second aspect of the present invention, a lithographic system is provided comprising the EUV radiation source according to the first aspect.

[00029] In a third aspect of the present invention, a method of generating EUV radiation is provided, the method comprising: providing a laser configured to produce radiation of a first wavelength; providing a nonlinear medium; directing radiation of the first wavelength to the nonlinear medium such that radiation of a second wavelength is produced via a nonlinear optical process at a radiation conversion region, wherein the second wavelength is longer than the first wavelength; providing a droplet of fuel at a plasma formation region; directing radiation of the second wavelength to the plasma formation region; and illuminating the fuel droplet in the plasma formation region with radiation of the second wavelength to convert the fuel droplet into a plasma.

[00030] The method may further comprise providing radiation of the first wavelength with a YAG-based laser, for example a Nd:YAG or Yb:YAG laser.

[00031] The method may further comprise producing radiation of the second wavelength wherein the second wavelength is in the range 1.4 to 12 micron. For example, using a Nd:YAG laser in combination with a gaseous methane nonlinear medium produces radiation at about 1.54 micron. Alternatively, a Yb:YAG laser in combination with a gaseous methane nonlinear medium will produce radiation at about 1.47 micron. Alternatively, using a Ho:YAG in combination with a gaseous methane nonlinear medium produces radiation at about 5.41 micron. Alternatively, using a Tm:YAG laser in combination with a gaseous methane nonlinear medium produces radiation at about 11.85 micron.

[00032] The method may further comprise producing radiation with a second wavelength in the range 1.4 – 2.4 micron.

[00033] The method may further comprise producing radiation with a second wavelength in the range 1.9 – 2.4 micron. For example, a Nd:YAG laser in combination with an optical parametric oscillator comprising a KTP crystal may produce radiation tuneable in the range 1.9 to 2.4 micron.

[00034] The method may further comprise producing radiation of a second wavelength wherein the second wavelength is in the range 1.4 – 2 micron. For example, using a Yb:YAG laser in combination with a gaseous hydrogen nonlinear medium produces radiation at about 1.80 micron. Alternatively, using a Nd:YAG laser in combination with a gaseous hydrogen nonlinear medium produces radiation at about 1.91 micron. The method using Nd:YAG or Yb:YAG lasers in these embodiments allows the production of an advantageous second wavelength at high powers.

[00035] In another embodiment the method produces radiation with a second wavelength about 1.9 micron. This provides an advantageous second wavelength at a high power.

[00036] The method may comprise illuminating the fuel droplets only by radiation of the second wavelength. Alternatively, the method may comprise illuminating the fuel droplets by both radiation at the first and second wavelengths. Using both radiation at the first and second wavelengths may be advantageous because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system unnecessarily.

[00037] The method may further comprise providing a nonlinear medium that is Raman-active. The method may further comprise using SRS to produce radiation of the second wavelength.

[00038] The method may further comprise providing a nonlinear medium that is gaseous, for example hydrogen or methane. The method may further comprise pressurizing the gas above atmospheric pressure.

[00039] In one embodiment of the present invention, the method further comprises replacing ionized gas in the radiation conversion region with non-ionized gas by providing a means of gas flow.

[00040] The method may further comprise using a pump to provide gas flow. The method may further comprise urging gas flow around a gas flow pathway.

[00041] The method may further comprise providing laminar gas flow across the radiation conversion region. Providing laminar gas flow is advantageous because it avoids refractive index changes in the gas. Refractive index changes may adversely affect the propagation of radiation through the gas. For example, laminar flow may be provided by shaping the gas flow pathway with a taper, or by regulating gas flow speed such that gas flow is limited to remain below a speed at which turbulent flow occurs.

[00042] The method may further comprise providing an optical parametric oscillator (OPO). The OPO may comprise the nonlinear medium. The nonlinear medium may be a nonlinear crystal. For example, the nonlinear medium may comprise one of: potassium titanyl arsenate (KTA), potassium titanyl phosphate (KTP), barium borate (BBO) or lithium niobate (LN), periodically poled KTP

(PPKPT), periodically poled LN (PPLN), rubidium doped KTP (RKTP), or periodically poled rubidium doped KTP (PPRKTP). The OPO may further comprise an optical cavity. The method may further comprise using second-order nonlinear optical interaction as the nonlinear process. Using an OPO, input radiation of a first wavelength may be converted into output radiation of a second, longer, wavelength. The output radiation wavelength may be tuneable. For example, a Nd:YAG laser in combination with a KTP crystal may produce output radiation with a second wavelength tunable in the range 1.9 to 2.4 micron.

[00043] The method may further comprise using an OPO to produce radiation of a third wavelength at the radiation conversion region. The third wavelength may be the same wavelength as the second wavelength, for example using a Nd:YAG laser in combination with a KTP crystal may be tuned to produce radiation of the second wavelength and third wavelength both about 2.1 micron. Alternatively, the second and third wavelengths may have different values.

[00044] The method may further comprise illuminating the fuel droplets by radiation of the third wavelength. Using radiation of the third wavelength in addition to radiation of the first and/or second wavelengths may be advantageous because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system unnecessarily.

[00045] The method may further comprise amplifying at least one of the radiation of the second wavelength or the radiation of the third wavelength, using an optical parametric amplifier (OPA). The method may further comprise using pump radiation to drive the amplification of radiation. The pump radiation may be provided by the laser configured to product radiation of the first wavelength, i.e. the pump radiation may have the same wavelength as the first wavelength. The pump radiation may be provided by a separate source i.e. the laser system may comprise a second laser. The pump radiation may have a fourth wavelength different to the first wavelength. The method may further comprise illuminating the fuel droplets by radiation of the fourth wavelength. Using radiation of the fourth wavelength in addition to radiation of the first and/or second and/or third wavelengths may be advantageous because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system unnecessarily.

[00046] The method may further comprise passing at least one of the radiation of the first wavelength, the radiation of the second wavelength or the radiation of the third wavelength, through a delay stage after the radiation conversion region. The delay stage may be configured to delay the arrival of at least a portion of the radiation at the plasma formation region. The delay stage may be configured to increase the temporal pulse length of radiation arriving at the plasma formation region. For example, by delaying the arrival of radiation of the third wavelength with respect to radiation of the second wavelength, the temporal pulse length of radiation arriving at the plasma formation region may be increased. The temporal pulse length is a measure of the duration of a pulse of radiation. A longer temporal pulse length may be advantageous for EUV conversion efficiency at the plasma formation region.

[00047] The method may further comprise using radiation of the first and/or second and/or third and/or fourth wavelength as a main pulse i.e. single pulse for EUV radiation formation at the plasma formation region. Alternatively, the method may further comprise using radiation of the first and/or second and/or third and/or fourth wavelength a main pulse in combination with an additional pulse of radiation, for example a pre-pulse to deform the fuel droplet prior to arrival of the main pulse. The pre-pulse may optimally shape the fuel droplet for more efficient EUV generation.

[00048] In another aspect of the present invention, a method is provided wherein the method comprises performing EUV lithography using EUV radiation produced according to any of the above methods.

[00049] It will be appreciated that any of the features of above-discussed aspects of the invention may, where appropriate, be combined with one or more other features of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[00050] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 depicts a lithographic system comprising a lithographic apparatus and a radiation source which includes a laser system according to an embodiment of the invention;
- Figure 2 depicts a laser system according to a first example implementation of the invention;
- Figure 3 is a schematic illustration of Raman scattering;
- Figure 4 depicts a gas flow system for increasing the efficiency of the production of radiation of a second wavelength;
- Figure 5 shows part of the gas flow system of Figure 4 in more detail;
- Figure 6 depicts a laser system according to a second example implementation of the invention; and
- Figure 6 depicts a laser system according to a third example implementation of the invention.

DETAILED DESCRIPTION

[00051] Figure 1 shows a lithographic system which comprises a radiation source SO according to an embodiment of the invention and a lithographic apparatus LA. The radiation source SO is configured to generate an extreme ultraviolet (EUV) radiation beam B. 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. The illumination system IL is configured to condition the radiation beam B before it is incident upon the patterning device MA. The projection system is configured to project the radiation beam B' (now patterned by the mask MA) onto the substrate W. The substrate W may include previously formed patterns. Where this is the case, the lithographic apparatus aligns the patterned radiation beam B' with a pattern previously formed on the substrate W.

[00052] The radiation source SO according to an embodiment of the invention, as schematically depicted in Figure 1, is of a type which may be referred to as a laser produced plasma (LPP) source. The radiation source SO comprises at least one laser system 1 which provides at least one laser beam 2. The at least one beam is incident upon a fuel, such as tin (Sn) which is provided from 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.

[00053] The laser 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.

[00054] EUV radiation emitted from the plasma will have a spectral profile. For example, EUV photons comprising EUV radiation beam B may have a range of energies. The range of energies may be affected by the properties of at least one laser beam 2 from the laser source 1. It is beneficial to optimize the spectral profile of emitted EUV radiation as required by the user. It is therefore beneficial to optimize the properties of the at least one laser beam 2 from the laser source 1. For example, a small range of energies, also known as a narrow spectral profile, may be desirable in EUV lithography. This is because radiation at wavelengths other than 13.5 nm is ineffective for EUV lithography, so represent a loss of energy. Radiation at wavelengths other than 13.5 nm may be removed from the radiation beam B. Emission at wavelengths other than 13.5 nm may also be known as 'out of band' emission. It may be desirable to reduce out of band emission, in particular to increase the conversion efficiency of the LPP process.

[00055] Conventional laser sources, for example CO₂ lasers, produce radiation with a wavelength around 10 micron. Radiation at this wavelength does not penetrate as deeply into the plasma, so produces a small range of EUV photon energies, also known as a narrow spectral profile. However, radiation at this wavelength experiences reflection from the fuel droplets. For example, when using tin droplets, around 30% of the radiation may be reflected. Reflected radiation implies that energy from the laser beam 2 is not being fully absorbed by the fuel droplets and hence is not being fully converted into EUV radiation. Reflected radiation implies a loss of input power and hence reduced conversion efficiency. Reflection may also damage equipment due to high-energy radiation being directed back to the laser system 1 or other apparatus. It is desirable to reduce reflection of laser radiation off the fuel droplet.

[00056] Radiation with a wavelength around 1 micron experiences negligible reflection from common fuel droplets. For example, when using tin droplets, around 0% of the radiation is reflected. However, 1 micron radiation penetrates deeper into the fuel plasma than 10 micron radiation. Deeper penetration may result in a wide range of EUV energies being produced due to the density, and hence

larger optical depth, within the plasma. EUV radiation at 13.5 nm with a narrow spectral profile is desirable, for example radiation with a wavelength within 1% of 13.5 nm. Radiation at other energies (also known as ‘out-of-band’ radiation) is not used for subsequent EUV lithography processes and implies a loss of output power. Out-of-band radiation results in a reduced conversion efficiency. It is desirable to reduce out-of-band radiation.

[00057] Intermediate wavelengths other than 1 micron and 10 micron form a favorable compromise between reflectivity and out-of-band radiation. The present invention allows for the production of intermediate wavelengths for use in an EUV radiation source.

[00058] The radiation source 50 according to the present invention comprises a laser system 1 which comprises a laser 30 and a nonlinear medium 32. The laser 30 is configured to emit radiation of a first wavelength 26 and deliver it to the nonlinear medium 32. The nonlinear medium 32 is configured to receive radiation of the first wavelength 26 and convert it into radiation of a second wavelength 28, wherein the second wavelength is longer than the first wavelength. The laser 30 is a pulsed laser.

[00059] The laser 30 may comprise an yttrium-aluminium-garnet (YAG) based laser. YAG is a crystalline material that, when doped with other materials, can be used as a lasing medium for solid-state lasers. These doping materials include, but are not limited to neodymium and ytterbium. Solid-state lasers using a lasing medium comprising YAG may be known as YAG-based lasers. YAG-based lasers can provide highly energetic pulses (above 1 J/pulse) at high repetition rates (around 50 kHz or more). YAG-based lasers are advantageous over CO₂ lasers because they have a high wall-plug efficiency, converting a larger proportion of electrical power to optical power. YAG-based lasers are also advantageous because they have a smaller footprint than CO₂ lasers, taking up less floor space which may be beneficial for space and/or transport and/or cost.

[00060] The laser 30 may comprise a neodymium-doped YAG (Nd:YAG) laser or a ytterbium-doped YAG (Yb:YAG) laser. The YAG-based lasers may emit at a wavelength around 1.0 micron. For example, Nd:YAG lasers emit at a wavelength of about 1.06 micron and Yb:YAG lasers emit at a wavelength of about 1.03 micron. However, a range of YAG lasers may be used with different emission wavelengths. For example, holmium-doped YAG (Ho:YAG) and thulium-doped YAG (Tm:YAG) emit at 2.10 micron and 2.00 micron respectively. However, Yb:YAG and Nd:YAG lasers tend to provide more power than Ho:YAG and Tm:YAG lasers so may be more advantageous.

[00061] Radiation of the first wavelength 26 is emitted by the laser 30 and received by the nonlinear medium 32. Radiation in the nonlinear medium 32 is converted to radiation of a second wavelength 28 via a nonlinear process. The nonlinear process may be Stimulated Raman Scattering. This is described in more detail further below and with reference to figure 3.

[00062] Radiation then exits the nonlinear medium 32 and comprises laser beam 2. The laser beam 2 is directed to the plasma formation region 4 to form EUV radiation.

[00063] The nonlinear process may convert all radiation of the first wavelength 26 to radiation of the second wavelength 28. In this case, the laser beam 2 consists of radiation of the second wavelength 28. The nonlinear process may convert only a fraction of radiation of the first wavelength 26 to radiation of the second wavelength 28. In this case, the laser beam 2 incident at the plasma formation region 4 may comprise radiation of the first wavelength 26 and radiation of the second wavelength. Alternatively, radiation of the first wavelength 26 may be removed, for example using filters or dichroic mirrors, such that it is not present when the laser beam 2 is incident at the plasma formation region 4.

[00064] The EUV radiation emitted by 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.

[00065] 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. The enclosing structure 9 of the radiation source SO contains the plasma formation region 4, the fuel emitter 3 and the collector 5.

[00066] The laser system 1 may be spatially separated from the enclosing structure 9 of the radiation source SO. Where this is the case, the laser beam 2 may be passed from the laser system 1 to the enclosing structure 9 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.

[00067] The radiation beam B passes from the radiation source SO into the illumination system IL, which is configured to condition the radiation beam. 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 radiation beam B with a desired cross-sectional shape and a desired angular intensity distribution. The radiation beam B passes from the illumination system IL and is incident upon the patterning device MA held by the support structure MT. The patterning device MA reflects and patterns the radiation beam B. 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.

[00068] Following reflection from the patterning device MA the patterned radiation beam B enters the projection system PS. The projection system comprises a plurality of mirrors 13, 14 which are

configured to project the radiation beam B onto a substrate W held by the substrate table WT. The projection system PS may apply a reduction factor to the radiation beam, forming an image with features that are smaller than corresponding features on the patterning device MA. A reduction factor of 4 may for example be applied. Although the projection system PS has two mirrors 13, 14 in Figure 1, the projection system may include any number of mirrors (e.g. six mirrors).

[00069] The radiation source SO, illumination system IL, and projection system PS may all be constructed and arranged such that they can be isolated from the external environment. A gas at a pressure below atmospheric pressure (e.g. hydrogen) may be provided in the enclosing structure 9 of the radiation source SO. A vacuum may be provided in illumination system IL and/or the projection system PS. A small amount of gas (e.g. hydrogen) at a pressure well below atmospheric pressure may be provided in the illumination system IL and/or the projection system PS.

[00070] The radiation source SO shown in Figure 1 may include components which are not illustrated. For example, a spectral filter may be provided in the radiation source. The spectral filter may be substantially transmissive for EUV radiation but substantially blocking for other wavelengths of radiation such as infrared radiation.

[00071] Figure 2 depicts part of the laser system 1 according to the present invention. The laser system 1 comprises a laser 30 configured to emit radiation of a first wavelength 26 and a nonlinear medium 32 through which radiation can travel.

[00072] Nonlinear media have optical properties, for example dielectric polarization, which respond to electromagnetic radiation in a nonlinear way. That is, nonlinear media respond to electromagnetic radiation differently to conventional media (for example transparent media). In response to electromagnetic radiation, nonlinear processes may occur in nonlinear materials which can lead to changes in the properties of the radiation such as wavelength, polarization or direction of travel. The present invention utilizes a change of wavelength in a nonlinear medium to produce radiation of a second wavelength 28 from radiation of a first wavelength 26

[00073] Radiation of the first wavelength 26 is provided by the laser 30. Radiation of the first wavelength 26 interacts with the nonlinear medium 32 at a radiation conversion region 44, producing radiation of a second wavelength 28 via a nonlinear process. The second wavelength is longer than the first wavelength. The nonlinear process enables production of wavelengths other than 1 and 10 micron, for example intermediate wavelengths between 1.4 and 12 micron.

[00074] In the depicted embodiment, the nonlinear medium 32 is a gas which is contained within a housing 50. In addition to containment, the housing 50 may also have other benefits, for example protecting the nonlinear medium 32 from contaminants.

[00075] In another embodiment, the laser 30 is a Nd:YAG laser. In this embodiment, the nonlinear process is Stimulated Raman Scattering (SRS) and the nonlinear medium 32 is hydrogen gas. In this embodiment, SRS within the radiation conversion region 44 converts radiation of the first

wavelength 26 into radiation of the second wavelength 28, wherein the second wavelength is about 1.91 micron.

[00076] In this embodiment, the hydrogen gas is pressurized within the range 3 – 10 bar. Many nonlinear optical processes are dependent on gas pressure. As such, gas pressure above atmospheric pressure may increase the radiation conversion efficiency. The gas pressure may also increase the gain in the nonlinear medium. The gas pressure may also improve the phase matching of radiation. The range of 1 – 20 bar has been found by the applicant to be suitable, but other gas pressures may be used. Alternatively, the gas pressure may be in the range 3 – 10 bar. Other embodiments which include a gaseous nonlinear medium may also use gas pressure above atmospheric pressure.

[00077] In a different embodiment, the laser 30 is a Yb:YAG laser. In this embodiment, the nonlinear process is SRS and the nonlinear medium 32 is hydrogen gas. In this instance, SRS within the radiation conversion region 44 converts radiation of the first wavelength 26 into radiation of the second wavelength 28, wherein the second wavelength is about 1.80 micron.

[00078] In a different embodiment, the laser is a Nd:YAG laser. In this embodiment, the nonlinear process is SRS and the nonlinear medium 32 is methane gas. In this instance, SRS within the radiation conversion region 44 converts radiation of the first wavelength 26 into radiation of the second wavelength 28, wherein the second wavelength is about 1.54 micron.

[00079] In a different embodiment, the laser 30 is a Yb:YAG laser. In this embodiment, the nonlinear process is SRS and the nonlinear medium 32 is methane gas. In this instance, SRS within the radiation conversion region 44 converts radiation of the first wavelength 26 into radiation of the second wavelength 28, wherein the second wavelength is about 1.47 micron.

[00080] In a different embodiment, the laser is a Ho:YAG laser. In this embodiment, the nonlinear process is SRS and the nonlinear medium 32 is methane gas. In this instance, SRS within the radiation conversion region 44 converts radiation of the first wavelength 26 into radiation of the second wavelength 28, wherein the second wavelength is about 5.41 micron. Radiation around 5.41 micron may provide a beneficial wavelength for illuminating the fuel droplets. However, a Ho:YAG laser embodiment may be less advantageous than the above embodiments using Nd:YAG or Yb:YAG lasers, as Nd:YAG and Yb:YAG lasers provide more power than Ho:YAG lasers.

[00081] In a different embodiment, the laser is a Tm:YAG laser. In this embodiment, the nonlinear process is SRS and the nonlinear medium 32 is hydrogen gas. In this instance, SRS within the radiation conversion region 44 converts radiation of the first wavelength 26 into radiation of the second wavelength 28, wherein the second wavelength is about 11.85 micron. In this embodiment, it may be beneficial to illuminate the fuel droplet with both radiation of the first wavelength 26 and radiation of the second wavelength 28 in a two pulse scheme, as will be discussed in more detail below. A Tm:YAG laser embodiment may be less advantageous than the above embodiments using Nd:YAG or Yb:YAG lasers, as Nd:YAG and Yb:YAG lasers provide more power than Tm:YAG lasers.

[00082] From the description above it should be understood that a range of lasers and/or nonlinear media may be used to achieve a range of second wavelengths. The desired range of second wavelengths is 1.4 to 12 micron. Radiation with a wavelength in the range 1.4 to 12 micron may be advantageous for EUV generation via LPP as it provides a compromise between reflectivity and out-of-band EUV emission.

[00083] The desired range of second wavelengths may be further defined as 1.4 to 2 micron. Second wavelengths in the range 1.4 to 2 micron are advantageous as they can be provided using a Yb:YAG or Nd:YAG laser. As a result, the laser system can provide radiation of a second wavelength in the range 1.4 to 2 micron at a high power. Radiation with a wavelength in the range 1.4 to 2 micron may be advantageous for EUV generation via LPP as it provides a compromise between reflectivity and out-of-band EUV emission.

[00084] The desired second wavelength provided may be further defined as about 1.9 micron, according to an embodiment of the invention as described above. This embodiment may provide a second wavelength that may be advantageous for conversion efficiency of the LPP process, with regard reflectivity and out-of-band radiation, at a high power.

[00085] Nonlinear processes occur more strongly with higher light intensities. A higher intensity can be achieved by increasing the fluence of the radiation 26. The fluence is a measure of energy per unit area for a beam of radiation. For a continuous wave (i.e. not pulsed) laser, the fluence is substantially constant with time. The fluence may be increased by increasing the intensity of the radiation 26. Alternatively or additionally, the fluence may be increased by reducing the diameter of the beam. With pulsed radiation, the fluence varies with time, so the maximum attained fluence, also known as the peak fluence, may be considered. The peak fluence can be increased by increasing the intensity of the radiation 26. Alternatively or additionally, the peak fluence may be increased by reducing the diameter of the beam. Alternatively or additionally, the peak fluence may be increased by decreasing the temporal duration of the pulse.

[00086] The diameter of the beam may be reduced by focusing the beam, for example using lenses. The laser system 1 may include a lens 31 to focus radiation of the first wavelength 26. The lens 31 will focus a beam of radiation to a minimum width, also known as a beam waist. The minimum achievable beam waist is dependent on the wavelength of the light and/or the focal length of the lens and/or the beam quality factor. The volume in which a beam is substantially focused may be known as a focal point. The focal point may form part of the radiation conversion region 44. Although a single lens 31 is depicted, in general any focusing optics may be used. Alternatively, in some embodiments focusing optics may not be required. For instance, it may be advantageous to provide an unfocused and/or demagnified image at the radiation conversion region 44.

[00087] The radiation exiting the radiation conversion region 44 is in the form of a radiation beam. The laser beam 2 comprises the radiation beam which exits the radiation conversion region. A corresponding lens 33 (or other focusing optics) may be placed to collect the laser beam 2 exiting the

radiation conversion region 44. The corresponding lens 33 may recollimate or refocus the laser beam 2 for delivery towards the plasma formation region 4. Alternatively, in some embodiments focusing optics may not be required. For instance, it may be advantageous to provide an unfocused and/or demagnified image at the plasma formation region 4.

5 [00088] In embodiments where focusing optics are used, the focusing optics 31, 33 may form part of the housing 50. Alternatively, the focusing optics 31, 33 may be separate from the housing 50.

[00089] As discussed above, the nonlinear process may convert all radiation of the first wavelength 26 to radiation of the second wavelength 28. Alternatively, the nonlinear process may convert a portion of the radiation of the first wavelength 26 to radiation of the second wavelength 28.

10 For example, in the above embodiments, SRS is used. SRS may convert up to 50% of radiation of the first wavelength 26 to the second wavelength 28. When this is the case, the laser beam 2 is a combination of radiation of the first wavelength 26 and the second wavelength 28.

[00090] In one embodiment, radiation of the first wavelength 26 is removed from the laser beam 2, for example using a filter and/or dichroic mirror. In this embodiment, only radiation of the second wavelength 28 is directed to the plasma formation region 4 and subsequently used to form EUV radiation.

15 [00091] In another embodiment, both radiation of the first wavelength 26 and second wavelength 28 are directed to the plasma formation region 4 and subsequently used to form EUV radiation. Illuminating fuel droplets with both radiation of the first wavelength 26 and second wavelength 28 may be beneficial because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system unnecessarily. However, to enable the use of two wavelengths of radiation, corrective optics may be required to correctly focus radiation of both wavelengths at the plasma formation region 4. The corrective optics used for this may include, but are not limited to, dichroic mirrors and/or achromats. Alternatively, in some embodiments focusing optics may not be required. For instance, it may be advantageous to deliver an unfocused and/or demagnified image at the plasma formation region 4.

20 [00092] Some conventional lithography methods use two pulses of radiation to illuminate the fuel droplets. These two pulses may be referred to as a pre-pulse and a main pulse respectively. The pre-pulse heats the fuel. In some cases the pre-pulse turns the fuel into a low density plasma. The pre-pulse may also shape the fuel. The main pulse is then incident on the modified fuel distribution. The main pulse creates the highly ionized plasma which emits EUV radiation. Two pulse illumination may be used in combination with some embodiments of the present invention, when illuminating fuel droplets with radiation of the first wavelength 26 and the second wavelength 28.

25 [00093] In an embodiment of the present invention, the laser system 1 comprises a Tm:YAG laser. In this embodiment, the nonlinear process is SRS and the nonlinear medium 32 is hydrogen gas. In this instance, SRS within the radiation conversion region 44 converts radiation of the first wavelength 26 into radiation of the second wavelength 28, wherein the second wavelength is about 11.85 micron,

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which is about 12 micron. In this embodiment, it may be beneficial to illuminate the fuel droplet with both radiation of the first wavelength 26 and radiation of the second wavelength 28 in two pulse illumination, using radiation of the first wavelength 26 as a pre-pulse and radiation of the second wavelength 28 as the main pulse.

5 [00094] Alternatively, radiation of the second wavelength 28 may be used as the pre-pulse and radiation of the first wavelength 26 may be used as the main pulse. In this instance, the arrival of radiation of the first wavelength 26 at the plasma formation region 4 may be delayed compared to the arrival of radiation of the second wavelength 28, for example by about a microsecond. In this embodiment, it may be beneficial to provide the radiation of the first wavelength 26 using a separate
10 laser (different to the laser 30) in order to provide a beneficial time delay between the pre-pulse and the main pulse. A first wavelength of about 2 micron and a second wavelength of about 12 micron may be beneficial for two pulse illumination. The first wavelength may provide an advantageous compromise between reflectivity and out-of-band radiation. The second wavelength is close to, and in LPP EUV generation it behaves in a similar way to, 10 micron radiation. The use of 10 micron
15 radiation is known in the production of EUV radiation using LPP sources.

[00095] Alternatively, other embodiments with alternative laser sources, for example other YAG based lasers may be used in combination with two pulse illumination. Alternatively or additionally, other second wavelengths in the range 1.4 to 12 micron may be used in combination with two pulse illumination.

20 [00096] As mentioned above, the nonlinear process may be Stimulated Raman Scattering (SRS). Raman Scattering is illustrated in Figure 3. When radiation of a first wavelength 26 excites a material, a particle nonlinear process may occur, where the material may be excited from a ground state 20 to a virtual state 21. In Raman scattering, this charge relaxes from the virtual state 21 to the ground state via an excited vibrational state 22. The difference in energy 24 between the ground state 20 and the
25 excited vibrational state 22 is equal to the energy of a resonant vibrational or rotational mode 24 in the material, also known as a Raman-active mode. A material with Raman-active modes may also be known as a Raman-active material.

[00097] As the charge relaxes via the excited vibrational state 22, it produces radiation at a second wavelength 28, where the second wavelength λ_2 is longer than the first wavelength λ_1 . The energy (E_1)
30 of a photon of radiation of the first wavelength may be calculated by $E_1 = hc/\lambda_1$, where h is the Planck constant and c is the speed of light in a vacuum. The energy (E_2) of a photon of radiation of the first wavelength may be calculated as $E_2 = hc/\lambda_2$. The difference in energy between radiation of the first wavelength (hc/λ_1) and radiation of the second wavelength (hc/λ_2) is equal to the energy of the Raman-active mode 24. The energy 24 is transferred to the material in the form of vibrational or
35 rotational energy. SRS may also be known as inelastic scattering or Stokes scattering.

[00098] Stimulated Raman Scattering (SRS) may be observed in nonlinear media using radiation with a high intensity such as laser radiation, which may be for example focused laser radiation. SRS is

analogous to Raman Scattering, but is stimulated rather than spontaneous. SRS may produce radiation of the second wavelength 28, where the radiation is coherent and propagates as a laser beam. Theoretically, up to 50% of all radiation of the first wavelength 26 may be converted into radiation of the second wavelength 28 using SRS.

5 [00099] The energies in the SRS process are determined by properties of the nonlinear media 32, in particular the energy difference 24 between the ground state 20 and the excited vibrational state 22. The energy difference 24 determines the energy change between radiation of the first wavelength 26 and radiation of the second wavelength 28. As a result, the second wavelength λ_2 depends on the first wavelength λ_1 , and the energy difference 24 in the nonlinear medium 32. The energy difference 24 is
10 intrinsic to a particular material, so to change it a different material may be used.

[000100] A range of lasers 30 and/or nonlinear media 32 may be used to alter the second wavelength λ_2 . In the above-described embodiments, production of a second wavelength in the range 1.4 – 12 micron is described. Radiation with a wavelength in this range may be advantageous for EUV generation via LPP as it provides a compromise between reflectivity and out-of-band EUV
15 emission.

[000101] The radiation conversion efficiency of nonlinear processes, for example SRS, may be limited by the formation of ions in the nonlinear medium 32 caused by the incident radiation 26. Ions and free electrons absorb radiation and are therefore detrimental to the propagation of radiation 26, 28 through the nonlinear medium 32. An ionized molecule must neutralize by recombining with an
20 electron before that molecule can provide SRS. Additionally, the molecule may be in a vibrationally excited state and must relax, for example via molecular collision, before SRS can occur. Neutralization and relaxation processes take time and so reduce the repetition rate at which nonlinear processes can occur. This in turn may lower the obtainable repetition rate of the output laser beam 2. This in turn may limit the obtainable EUV power, which is dependent on the repetition rate of
25 radiation delivered to the plasma formation region 4. .

[000102] Contaminant particles, for example dust, in the nonlinear medium 32 may have surface charges that may be released through electric discharge when irradiated by radiation. When a released charge is present, it may interact with other molecules in the nonlinear medium 32 and cause an avalanche ionization event. An avalanche ionization event may rapidly ionize surrounding molecules.
30 A laser-produced plasma may also be directly created from such particles.

[000103] Ionization within the nonlinear medium 32 may be somewhat avoided by removing contaminants, for example dust, from the nonlinear medium 32. However, ionization is an intrinsic process and will still occur in the absence of contaminants. Ionization may occur due to multiphoton effects. For example, a molecule may absorb multiple photons of radiation and ionize. It may be
35 desirable to inhibit ionization in the nonlinear medium. It may be desirable to reduce the effect the ionization of molecules has on the radiation conversion efficiency of nonlinear processes.

[000104] To reduce the effect ionized molecules have on the radiation conversion efficiency, it is desirable to replace ionized molecules with non-ionized molecules in the radiation conversion region 44. A gas flow system 40 may be provided desirable to replace ionized molecules with non-ionized molecules in the radiation conversion region 44. One embodiment of such a gas flow system 40 is shown in figure 4, where a pump 42 provides circulation of the gas 32 around a loop. The loop may be defined at least in part by the housing 50 of the nonlinear medium 32.

[000105] Circulation is provided such that the gas 32 flows generally perpendicular to the direction of laser radiation 26 within the radiation conversion region 44. In figure 4, the direction of laser radiation 26 is depicted as travelling into the page. The gas 32 may for, for example, along the axis A within the radiation conversion region 44. As such, any ionized gas within the radiation conversion region 44 is urged away from the radiation conversion region 44 and circulates towards the pump 42. The pump 42 and associated gas flow urges non-ionized gas into the radiation conversion region 44 to replace the ionized gas.

[000106] The pump 42 may also comprise a filter to remove dust or other contaminants. The pump 42 may also comprise an ion scrubber to remove ionized material as it passes through the pump 42.

[000107] Free electrons may be produced in multi-photoionization processes. Free electrons may absorb radiation and hence reduce the propagation of radiation of incoming or outgoing radiation. It may be beneficial to remove free electrons. Additional material may be added to the nonlinear medium, for instance by providing a pre-mixed solution of a gaseous nonlinear medium with an additional gaseous material. The additional material may aid the remove free electrons. The free electrons may be removed by, for example, the binding of free electrons to a molecular species within the additional material. The free electrons may be removed by, for example, absorption. Examples of materials that may aid the removal of free electrons are sulfur hexafluoride (SF₆) or carbon dioxide (CO₂). Alternatively, the material may enhance vibrational and/or translational relaxation of the gas 32 and hence reduce relaxation times. Examples of materials that may enhance vibrational and/or translational relaxation of the gas 32 are noble gases such as helium, neon or argon.

[000108] Figure 5 shows a magnified view of the radiation conversion region 44 according to the above embodiment of the invention, wherein a gas flow system 40 is provided in combination with a gaseous nonlinear medium 32. Radiation of the first wavelength 26 is focused by a lens 31, enters the housing 50, and hence enters the nonlinear medium 32. SRS occurs within the radiation conversion region 44, and produces radiation of the second wavelength 28 which exits the nonlinear medium 32, exits the housing 50, and is recollimated by a second lens 33 for delivery to the plasma formation region 4. Arrows show the movement of the gaseous nonlinear medium 32 urged by the pump. The direction of movement of the gaseous nonlinear medium 32 is substantially perpendicular to the direction of travel of radiation 26, 28. The direction of movement of the gaseous nonlinear medium is substantially parallel to axis A.

[000109] The speed of travel of the gas 32 may be chosen to ensure that ionized gas is fully replaced between successive pulses of radiation 26. As such, the speed depends on the repetition rate of pulsed radiation and the diameter W of the focused radiation beam 26. The desired speed can be approximated as the beam diameter W multiplied by the laser repetition rate. For example, with a laser focus diameter of 500 micron and a laser repetition rate of 50 kHz, a gas flow speed of 25 m/s is desired. Speeds below this will result in some, but not all, ionized gas being replaced between successive pulses of radiation. It is desirable for all ionized gas to be fully replaced. Partial replacement, for example using intermediate speeds between 0 m/s and 25 m/s, will yield a partial improvement in repetition rates and SRS efficiency. Intermediate speeds may be chosen by the user to sufficiently improve the repetition rate and SRS efficiency enough for the user's needs.

[000110] An upper limit is present on the gas flow speed, defined by the speed at which gas flow is laminar within the radiation conversion region 44. Turbulent gas flow may lead to inhomogeneous refractive indices across radiation conversion region 44 which may be detrimental to the propagation of both radiation of the first wavelength 26 and radiation of the second wavelength 28.

[000111] According to a method of the present invention, a gas flow speed is provided such that the gas flow is laminar within the radiation conversion region 44. For example, in the depicted embodiment the sides of the housing 50 proximal to the radiation conversion region 44 are tapered. Tapering the housing 50 ensures the gas 32 does not experience any abrupt changes in speed or direction, reducing the chance of turbulent gas flow. A taper may be linear or include some curvature. Alternatively or additionally, laminar flow may be enabled using other methods such as regulating gas flow speed such that gas flow is limited to remain below a speed at which turbulent flow occurs.

[000112] Although specific reference may be made to gaseous nonlinear media in the embodiments above, the nonlinear medium may be in other phase states. For example, SRS may be provided using a nonlinear medium which comprises a cryogenically formed solid, for example solid hydrogen, in particular solid parahydrogen.

[000113] While specific reference may be made to Stimulated Raman Scattering (SRS) in the embodiments above, other nonlinear processes may be used.

[000114] In an alternative embodiment of the invention, the laser system 1 may comprise an optical parametric oscillator (OPO). OPOs are known in the art and convert input radiation into two portions of output radiation with longer wavelength than the input radiation. When considering OPOs, the input radiation may be referred to as pump radiation, and the two portions of output radiation may be referred to as signal radiation and idler radiation. These may also be referred to simply as the pump, signal and idler respectively.

[000115] With reference to Figure 6, pump radiation of the first wavelength 26 may be input into an OPO which may comprise for example a nonlinear crystal. Second-order nonlinear optical interactions may convert the radiation of the first wavelength 26 into radiation of a second wavelength 28 (the signal) and radiation of a third wavelength 29 (the idler). The OPO process differs from the

SRS process described above because, for example, whereas in SRS the difference in energy between radiation of the first and second wavelengths is transferred to the material in the form of rotation or vibrational energy, in an OPO this difference in energy is converted into radiation of the third wavelength. The third wavelength may be denoted as λ_3 .

5 [000116] The energy (E_1) of a photon of radiation of the first wavelength 26 (the pump) may be calculated by $E_1 = hc/\lambda_1$, where h is the Planck constant and c is the speed of light in a vacuum. Pump radiation may be provided by a laser, for example a YAG-based laser. YAG-based lasers are advantageous because they have a high wall-plug efficiency, converting a larger proportion of electrical power to optical power. YAG-based lasers are also advantageous because they have a small footprint, taking up less floor space which may be beneficial for space and/or transport and/or cost.

10 [000117] The energy (E_2) of a photon of radiation of the second wavelength 28 may be calculated as $E_2 = hc/\lambda_2$. The energy (E_3) of a photon of radiation of the third wavelength 29 may be calculated as $E_3 = hc/\lambda_3$. In an OPO, the energy of the radiation of the first wavelength is equal to the sum of energies of the second and third wavelengths i.e. $hc/\lambda_1 = hc/\lambda_2 + hc/\lambda_3$. In some cases, the third wavelength may be chosen so that it has the same wavelength as the second wavelength, such that the input pump radiation is converted only into radiation of the second wavelength. This specific case may be referred to as degeneracy, or as having a degenerate signal and idler. Alternatively, the second and third wavelengths may be different.

15 [000118] An embodiment of the present invention using an OPO is depicted in Figure 6. A laser system 1 is shown, comprising a laser 30 used to generate radiation of the first wavelength, and an OPO 60 comprising a nonlinear crystal 32 disposed within an optical cavity defined between two mirrors 62. Radiation of the first wavelength is directed to the OPO where second-order nonlinear optical interactions occur in the nonlinear crystal 32, within a radiation conversion region 44, and convert some radiation of the first wavelength into radiation of the second, and optionally third, wavelengths. The length of the optical cavity in this instance may be understood to be the distance between the two mirrors 62. The OPO 60 in Figure 6 is not drawn to scale, and as such the nonlinear crystal 32 may occupy, for example, a smaller portion of the optical cavity. The mirrors 62 may be partially transmissive, such that they transmit some radiation out of the optical cavity and reflect some radiation back through the optical cavity. The mirrors 62 may be selected to transmit a specific wavelength or range of wavelengths. For example, the mirrors 62 may be dichroic mirrors. The mirrors 62 may be configured to transmit radiation of the second wavelength and reflect radiation of the first wavelength i.e. transmit the signal and reflect the pump radiation. This may be advantageous as, by reflecting the pump, it can pass through the nonlinear crystal 32 again and create more radiation of the second wavelength. The mirrors 62 may also be configured to selectively reflect or transmit radiation of the third wavelength.

30 [000119] The radiation exiting the OPO 60 forms a laser beam 2 which may comprise radiation of the first and/or second and/or third wavelengths. The laser beam 2 may then be delivered to the

plasma formation region 4 (see Figure 1). The laser beam 2 may be focused at the plasma formation region 4, for example using focusing optics such as a lens. Alternatively, no focusing optics may be used. For example, it may be advantageous to deliver an unfocused and/or demagnified image at the plasma formation region 4.

5 [000120] Radiation of the first and third wavelengths may be removed from the laser beam 2, for example using a band-pass filter and/or dichroic mirror. In this case, only radiation of the second wavelength is directed to the plasma formation region and subsequently used to form EUV radiation. Alternatively, radiation of the first wavelength may be removed from the laser beam 2, for example using a filter and/or dichroic mirror. In this case, only radiation of the second and third wavelengths
10 are directed to the plasma formation region and subsequently used to form EUV radiation. Alternatively, radiation of the first, second and third wavelengths may be directed to the plasma formation region and subsequently used to form EUV radiation. Illuminating fuel droplets with radiation of the first, second and third wavelengths may be beneficial because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or removed from the system
15 unnecessarily. In these examples, the dichroic mirror could be a mirror 62 defining the optical cavity in the OPO as shown in Figure 6. Alternatively or additionally, a mirror and/or filter may be provided after radiation has exited the OPO.

[000121] To enable the use of two or three wavelengths of radiation to illuminate fuel droplets, corrective optics may be required to correctly deliver radiation of both wavelengths at the plasma
20 formation region 4. The corrective optics used for this may include, but are not limited to, dichroic mirrors and/or achromats.

[000122] The second and third wavelengths may be selected. For example, the second and third wavelengths can be selected by selecting the first wavelength i.e. by changing the pump laser 30. The pump laser 30 may for example be a Nd:YAG or Yb:YAG laser which emit radiation at about 1
25 micron.

[000123] Alternatively or in addition, the second and third wavelengths can be selected by changing the nonlinear medium 32 in the OPO 60. The nonlinear medium 32 may be a nonlinear crystal, for example potassium titanyl arsenate (KTA), potassium titanyl phosphate (KTP), barium borate (BBO) or lithium niobate (LN), periodically poled KTP (PPKTP), periodically poled LN (PPLN), rubidium doped KTP (RKTP), or periodically poled rubidium doped KTP (PPRKTP). This
30 list is non-exhaustive and there are many other nonlinear crystals known in the art which may be used depending on the requirements of the user.

[000124] Alternatively or in addition, the second and third wavelengths can be selected by altering the phase matching properties of the nonlinear crystal. Altering the phase matching properties of the
35 nonlinear crystal allows for tunable selection of the second and third wavelengths. The wavelengths may be tunable within a range, where the range may be dependent on factors such as the pump wavelength, pump polarization, and the nonlinear crystal material. The phase matching properties of

the nonlinear crystal, and hence the second and third wavelengths, can be selected in a number of ways. For example, the temperature of the nonlinear crystal may be altered. Altering the temperature may be particularly advantageous for tuning the second and third wavelengths when using periodically poled nonlinear media. Alternatively or in addition, the length of the optical cavity may be altered. Alternatively or in addition, a dispersive element such as a grating may be provided. Alternatively or in addition, the angular orientation of the nonlinear crystal may be altered with respect to the radiation beam, for example by altering the orientation of the optical axis of the crystal and/or the polarization of the radiation beam.

[000125] In an example implementation, a Nd:YAG laser in combination with an OPO comprising a PPRKPT crystal may produce emission of a second wavelength that is tunable in the range 1.9 – 2.4 micron. The emission may be tuned as stated above, for example by altering the length of the optical cavity. A specific example may be where the second and third wavelengths are chosen to be equal, with a wavelength around 2.1 micron.

[000126] OPOs can be used to convert radiation with short temporal pulse lengths and/or high repetition rates, with high conversion efficiency. A conversion efficiency of over 35% may be achieved, for example using a large aperture PPRKPT crystal in combination with a Nd:YAG laser. Efficiency in this instance is the amount of radiation of the second wavelength exiting the OPO compared to the amount of radiation of the first wavelength entering the OPO. In use, and when using radiation of the first, second and third wavelength to illuminate fuel droplets, this means that around 35% of the radiation delivered to the fuel droplets may be radiation of the second wavelength, and around 65% of radiation delivered to the fuel droplets may be radiation of the first and third wavelengths.

[000127] It may be desirable to increase the conversion efficiency of the laser system 1.

[000128] Radiation of the first wavelength may be recovered, for example by separating it from the main radiation beam using a dichroic mirror and redirecting it back into the OPO to produce more radiation of the second wavelength. In this instance, the recovering of pump radiation may lead to a conversion efficiency close to 100% efficient. The dichroic mirror may be a mirror defining the optical cavity in the OPO as shown in Figure 6. Alternatively or additionally, a mirror and/or filter may be provided after radiation has exited the OPO.

[000129] Alternatively, an example laser system used to increase conversion efficiencies is shown in Figure 7 which depicts a laser system 1 comprising an OPO 60 and an optical parametric amplifier (OPA) 68. OPAs are known in the art and are used to amplify a radiation beam when driven by an additional pump beam. The OPA 68 comprises another nonlinear medium (not shown) and uses second-order nonlinear interactions to amplify radiation.

[000130] In this embodiment, radiation of a first wavelength 26 is provided by a first laser 30a and delivered to an OPO 60. The radiation provided by laser 30a may be referred to as the first pump or first pump beam 26. The OPO converts this radiation into a radiation beam 2a, comprising radiation

of the first, second and, optionally, third wavelengths. A beam-splitter, for example a dichroic mirror, may then be used to separate the radiation beam into two portions 2b, 2c. The first portion 2b comprises radiation of the second wavelength i.e. the OPO signal. The second portion 2c comprises radiation of the first and, optionally, third wavelengths i.e. the first pump 26 and the OPO idler.

5 [000131] Radiation of a fourth wavelength 66 may be provided by a second laser 30b. Radiation of the fourth wavelength 66 may also be known as the second pump 66. The fourth wavelength may be chosen such that it is the same as the first wavelength. In the depicted example, two separate lasers 30a, 30b are used to provide the first pump 26 and the second pump 66. However, in an alternative implementation both first 26 and second 66 pump beams may be provided by a single laser, for
10 example by splitting the beam into two portions and delivering one to the OPO and one to the OPA. This may be advantageous for simplicity and a reduced footprint.

[000132] The second pump 66 and the OPO signal 2b are delivered to the OPA 68, for example using dichroic mirrors to combine them into a single radiation beam 2d. The OPA 68 converts a portion of the incoming radiation beam 2d into radiation of the second wavelength (i.e. the amplified
15 OPO signal 2b) and radiation of a fifth wavelength. Radiation of the fifth wavelength may be produced as, similar to in an OPO, the nonlinear interactions produce an additional radiation beam known as an OPA idler beam. As a result, the radiation exiting the OPA (the OPA output beam 2e) comprises radiation of the fourth wavelength (the second pump beam 66), radiation of the second wavelength (the amplified OPO signal 2b), and radiation of the fifth wavelength (the OPA idler).
20 Similar to in an OPO, the wavelengths produced by an OPA are tunable as known in the art.

[000133] The OPA output beam 2e is combined with the second portion 2c to form radiation beam 2f. Radiation beam 2f may then be delivered to the plasma formation region. Radiation beam 2f will
25 comprise radiation of the second wavelength. Due to the amplification from the OPA 68, the radiation beam 2f will contain more radiation of the second wavelength than using an OPO 60 alone. Using an OPA may increase the conversion efficiency to over 50%. Efficiency in this instance is the amount of radiation of the second wavelength exiting the OPA compared to the amount of radiation in the first and second pump beams.

[000134] Radiation beam 2f may also comprise radiation of the first and/or third and/or fourth and/or fifth wavelengths. Radiation of the first and/or third and/or fourth and/or fifth wavelengths may
30 be removed from the radiation beam 2f, for example using a filter and/or dichroic mirror. Alternatively, radiation of the first, second, third, fourth and fifth wavelengths may be directed to the plasma formation region and subsequently used to form EUV radiation. Illuminating fuel droplets with radiation of the first, second, third, fourth and fifth wavelengths may be beneficial because it utilizes all available radiation to illuminate fuel droplets. That is, no optical power is wasted or
35 removed from the system unnecessarily.

[000135] The fifth wavelength may be chosen such that it is the same as the third wavelength, for example by using the same wavelength for the first and second pump beams and optimizing the OPA such that it produces the same signal and idler wavelengths as the OPO.

[000136] In one particular example, the first 26 and second 66 pump may have the same wavelength i.e. the first wavelength. The OPO 60 may be optimized such that the signal and idler are degenerate i.e. the second and third wavelengths are the same. The OPA 68 may be optimized such that the signal and idler are degenerate i.e. the second and fifth wavelengths are the same, and such that the fifth wavelength is equal to the second wavelength. As such, in this example, the radiation beam 2f comprises radiation of the first and second wavelengths. In this example, due to amplification from the OPA 68, the conversion efficiency of radiation of the first wavelength to radiation of the second wavelength may be over 50%. In this case, fuel droplets may be illuminated by radiation of the second wavelength, or by radiation of the first and second wavelengths.

[000137] In a specific example, a single Nd:YAG laser may be used to provide the first and second pump beams 26, 66 at a first wavelength of 1 micron. The OPO and OPA may be tuned to produce degenerate idler and signal beams at 1.9 micron. As such, the radiation beam 2f may comprise radiation at 1 micron and 1.9 micron. Alternatively, the OPA and OPO may be tuned to produce a signal beam i.e. radiation of the second wavelength in the range 1.9 to 2.4 micron.

[000138] Some known lithography methods use two pulses of radiation to illuminate the fuel droplets. These two pulses may be referred to as a pre-pulse and a main pulse respectively. The pre-pulse heats the fuel. In some cases the pre-pulse turns the fuel into a low density plasma. The pre-pulse may also shape the fuel, which may be referred to as modifying the fuel distribution. The main pulse may then be incident on the modified fuel distribution. The main pulse creates the highly ionized plasma which emits EUV radiation. Two pulse illumination may be used in combination with the above examples, for example providing a pre-pulse from an additional radiation source and using the radiation beam 2, 2f as the main pulse. The additional radiation source may be the second laser 30b. Alternatively, a separate radiation source may be provided, for example an addition laser such as a YAG-based laser. Alternatively, the radiation beam 2, 2f may be used for main-pulse-only operation i.e. no pre-pulse is used.

[000139] Conventional OPOs and OPAs typically provide radiation with short temporal pulse lengths, for example in the range 3 to 5 nanoseconds. The temporal pulse length is a measure of the duration of a pulse of radiation. Temporal pulse length may be referred to simply as pulse length. The pulse length may be associated with the pulse duration of the first and second pump beams i.e. the pulse length provided by the lasers 30a, 30b, which may typically be in the range 6 to 8 nanoseconds.

[000140] A short pulse length may reduce the EUV conversion efficiency of the radiation in radiation beam 2, 2f into EUV radiation. A longer pulse may increase the EUV conversion efficiency. For example, a pulse length in the range 50 to 150 nanoseconds may increase EUV conversion efficiency. The pulse length may be increased by using a laser 30a, 30b with a longer pulse length, for

example a pulse length in the range 50 to 150 nanoseconds. YAG-based lasers with pulse lengths in this range are available. Additionally or alternatively, the OPO can be optimized for pulse lengths in the range 50 to 150 nanoseconds, for example by changing the length of the optical cavity.

[000141] Additionally or alternatively, the pulse length may be increased by delaying one or more portions of the radiation beam with respect another portion of the beam. This may also be referred to as pulse stretching.

[000142] Pulse stretching may be performed by using a beam splitter to split a radiation beam into a first and second portion. The first portion may be directed to an optical delay arrangement which applies an optical delay to the first portion. The first and second portion are then recombined into a modified radiation beam, and delivered to a target point. The first portion of the modified radiation beam arrives at the target point after the second portion due to the optical delay, resulting in an increased total temporal pulse length i.e. pulse stretching. This method can hence be used to increase the pulse length, for example by a factor of two or three times, by spreading out the arrival times of different portions of the beam.

[000143] The beam splitter may be a dichroic mirror configured to reflect radiation of the first and/or second and/or third and/or fourth and/or fifth radiation. The beam splitter may direct radiation of a specific wavelength to the optical delay arrangement to apply a delay. Multiple beam splitters may be used, and multiple optical delay arrangements may be used. In one example, radiation of the first wavelength may be transmitted, radiation of the second wavelength may be directed to a first optical delay arrangement and delayed by a first delay time, and radiation of the third wavelength may be directed to a second optical delay arrangement and delayed by a second delay time.

[000144] Alternatively the beam splitter may be a partially transmissive mirror, for example a half-silvered mirror. In this instance, 50% of the radiation beam will be reflected and 50% will be transmitted, but with little to no separation of wavelengths. In this instance, 50% of the radiation beam may be delivered to an optical delay arrangement. As with the above example, multiple beam splitters may be used and multiple optical delay arrangements may be used. The partially transmissive mirror may transmit a different proportion of the radiation beam, for example but not limited to, 1%, 10% or 40%.

[000145] A portion of the radiation beam may pass through an optical arrangement multiple times. For example, a first portion of the radiation beam may pass through an optical arrangement once, whereas a second portion of the radiation beam may be redirected back into the optical arrangement and hence pass through the optical arrangement twice. Multiple passes through an optical arrangement will increase the delay time of a portion of the radiation beam and hence increase the total temporal pulse length of the modified radiation beam.

[000146] The optical delay arrangement used to apply an optical delay may be a delay line, also known as a delay stage. Known delay lines are described in more detail in US7326948, which is hereby incorporated by reference in its entirety. In brief, the delay line may be in the form of a

plurality of mirrors to add distance to the path travelled by a first portion of a beam. The delay line may further comprise a beam splitter to direct the first portion of the beam to the delay line and permit a second portion of the beam to travel unimpeded.

[000147] It has been described above therefore, how nonlinear optical processes can be used with an OPO to produce radiation of a second wavelength longer than a first wavelength. It has also been described above how this may be beneficial to the production of EUV radiation by LPP. The above examples of OPO use are optimized for radiation of a second wavelength tunable in the range 1.9 to 2.4 micron. In combination with the embodiments using SRS, the range of achievable wavelengths may be extended to from 1.4 to 2.4, and further from 1.4 to 12 micron.

[000148] Although specific reference may be made in this text to mirrors, any suitable optical elements may be used. For example, the element may be a grating, a beam cube or any other dispersive element. In some cases the mirrors may be beamsplitting, for example a dichroic mirror, a half-silvered mirror, or any other beam splitting element known in the art.

[000149] Although specific reference may be made to YAG-based lasers, any suitable lasers may be used. In this instance, any suitable laser may be one that emits at a wavelength that enables production of a second wavelength in the range 1.4 – 12 micron using nonlinear processes such as those described above. For example, glass lasers may be used, in particular neodymium doped glass lasers, as they emit at around 1 micron, similar to conventional YAG-based lasers.

[000150] 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 apparatus may be generally referred to as lithographic tools. Such a lithographic tool may use vacuum conditions or ambient (non-vacuum) conditions.

[000151] 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.

CLAIMS

1. An EUV radiation source of a laser-produced-plasma type, comprising:
 - a fuel emitter configured to produce fuel droplets; and
 - a laser system configured to illuminate a fuel droplet with radiation for converting the fuel droplet into a plasma at a plasma formation region;wherein the laser system comprises:
 - a laser configured to produce radiation of a first wavelength; and
 - a nonlinear medium configured to receive radiation of the first wavelength, produce radiation of a second wavelength using a nonlinear optical process at a radiation conversion region, and deliver radiation of the second wavelength to the plasma formation region;wherein the second wavelength is longer than the first wavelength.
2. The EUV radiation source of claim 1, wherein the laser comprises a YAG-based laser.
3. The EUV radiation source of claim 1 or 2, wherein the second wavelength is in the range 1.4 to 12 micron.
4. The EUV radiation source of any preceding claim, wherein the second wavelength is in the range 1.4 to 2.4 micron.
5. The EUV radiation source of any preceding claim, wherein the second wavelength is in the range 1.9 to 2.4 micron.
6. The EUV radiation source of any preceding claim, wherein the second wavelength is about 1.9 micron.
7. The EUV radiation source of any preceding claim, wherein the fuel droplets are also illuminated by radiation of the first wavelength.
8. The EUV radiation source of claim 1, wherein the nonlinear medium comprises a Raman-active material and the nonlinear optical process is stimulated Raman scattering.
9. The EUV radiation source of claim 8, wherein the nonlinear medium comprises a gas.
10. The EUV radiation source of claims 8 or 9, wherein the nonlinear medium comprises hydrogen.

11. The EUV radiation source of claim 9, further comprising a flow system configured to replace ionized gas in the radiation conversion region with non-ionized gas.
12. The EUV radiation source of claim 11, wherein the flow system comprises a gas flow pathway and a pump configured to circulate gas around the gas flow pathway.
13. The EUV radiation source of any of claims 1 to 7, wherein the laser system further comprises an optical parametric oscillator, and wherein the optical parametric oscillator comprises the nonlinear medium.
14. The EUV radiation source of claim 13, wherein the nonlinear process is further configured to produce radiation of a third wavelength at the radiation conversion region.
15. The EUV radiation source of claim 14, wherein the fuel droplets are also illuminated by radiation of the third wavelength.
16. The EUV radiation source of any of claims 13 to 15, further comprising an optical parametric amplifier to amplify at least one of the radiation of the first wavelength, the radiation of the second wavelength, or the radiation of the third wavelength.
17. The EUV radiation source of any preceding claim, further comprising a delay stage after the radiation conversion region.
18. A lithographic system comprising the EUV radiation source of any preceding claim.
19. A method of generating EUV radiation comprising:
 - providing a laser configured to produce radiation of a first wavelength;
 - providing a nonlinear medium;
 - directing radiation of the first wavelength to the nonlinear medium such that radiation of a second wavelength is produced via a nonlinear optical process at a radiation conversion region, wherein the second wavelength is longer than the first wavelength;
 - providing a droplet of fuel at a plasma formation region;
 - directing radiation of the second wavelength to the plasma formation region; and
 - illuminating the fuel droplet in the plasma formation region with radiation of the second wavelength to convert the fuel droplet into a plasma.

20. The method according to claim 19, wherein the method further comprises providing radiation of the first wavelength with a YAG-based laser.
21. The method according to claim 19 or 20, wherein the method further comprises producing radiation of the second wavelength wherein the second wavelength is in the range 1.4 to 12 micron.
22. The method according to any of claims 19 to 21, wherein the method further comprises producing radiation of the second wavelength wherein the second wavelength is in the range 1.4 to 2.4 micron.
23. The method according to any of claims 19 to 22, wherein the method further comprises producing radiation of the second wavelength wherein the second wavelength is in the range 1.9 to 2.4 micron.
24. The method according to any of claims 19 to 23, wherein the method further comprises producing radiation of the second wavelength wherein the second wavelength is about 1.9 micron.
25. The method according to any of claims 19 to 24, wherein the method further comprises illuminating fuel droplets by radiation of the first wavelength.
26. The method according to claim 19, wherein the method further comprises providing a Raman-active material and using stimulated Raman scattering to produce radiation of the second wavelength.
27. The method according to claim 19 or 26, wherein the method comprises providing a nonlinear medium that is gaseous.
28. The method according to claim 26 or 27, wherein the method comprises providing a nonlinear medium that comprises hydrogen.
29. The method according to claim 27, wherein the method further comprises replacing ionized gas in the radiation conversion region with non-ionized gas by providing a means of gas flow.
30. The method according to claim 29, wherein the method further comprises using a pump to provide gas flow.

31. The method according to claim 30, wherein the method further comprises providing laminar gas flow across the radiation conversion region.
32. The method according to any of claims 18 to 23, wherein the method further comprises providing an optical parametric oscillator comprising the nonlinear medium to produce radiation of the second wavelength.
33. The method according to any of claim 30, wherein the method further comprises using the optical parametric oscillator to further produce radiation of a third wavelength.
34. The method according to claim 33, wherein the method further comprises illuminating fuel droplets by radiation of the third wavelength.
35. The method according to any of claims 32 to 34, wherein the method further comprises amplifying at least one of the radiation of the first wavelength, the radiation of the second wavelength, or the radiation of the third wavelength, using an optical parametric amplifier.
36. The method according to any of claims 19 to 35, wherein the method further comprises passing at least one of the radiation of the first wavelength, the radiation of the second wavelength, or the radiation of the third wavelength through a delay stage.
37. A method of performing EUV lithography using EUV radiation produced according to any of claims 19 to 36.

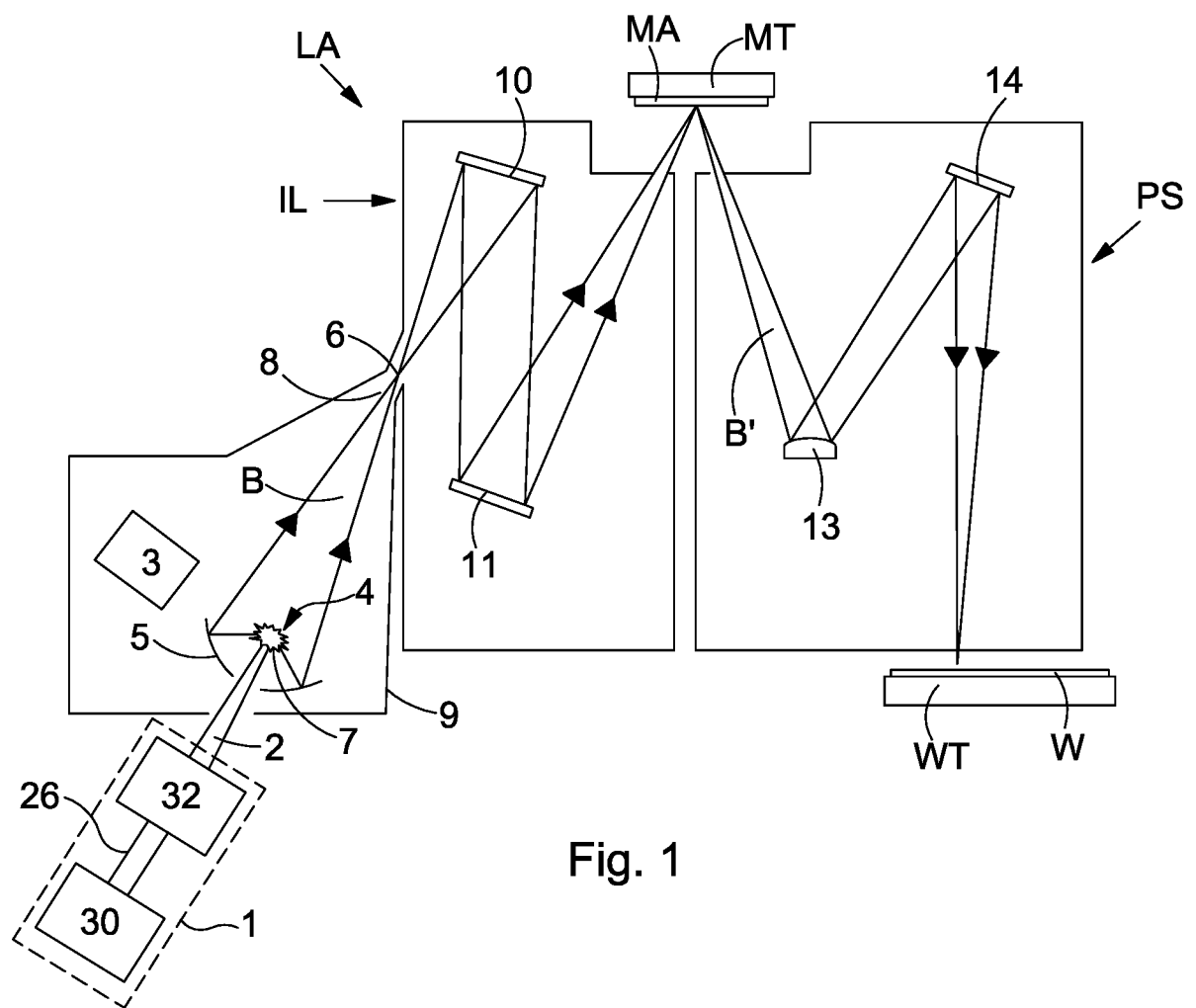


Fig. 1

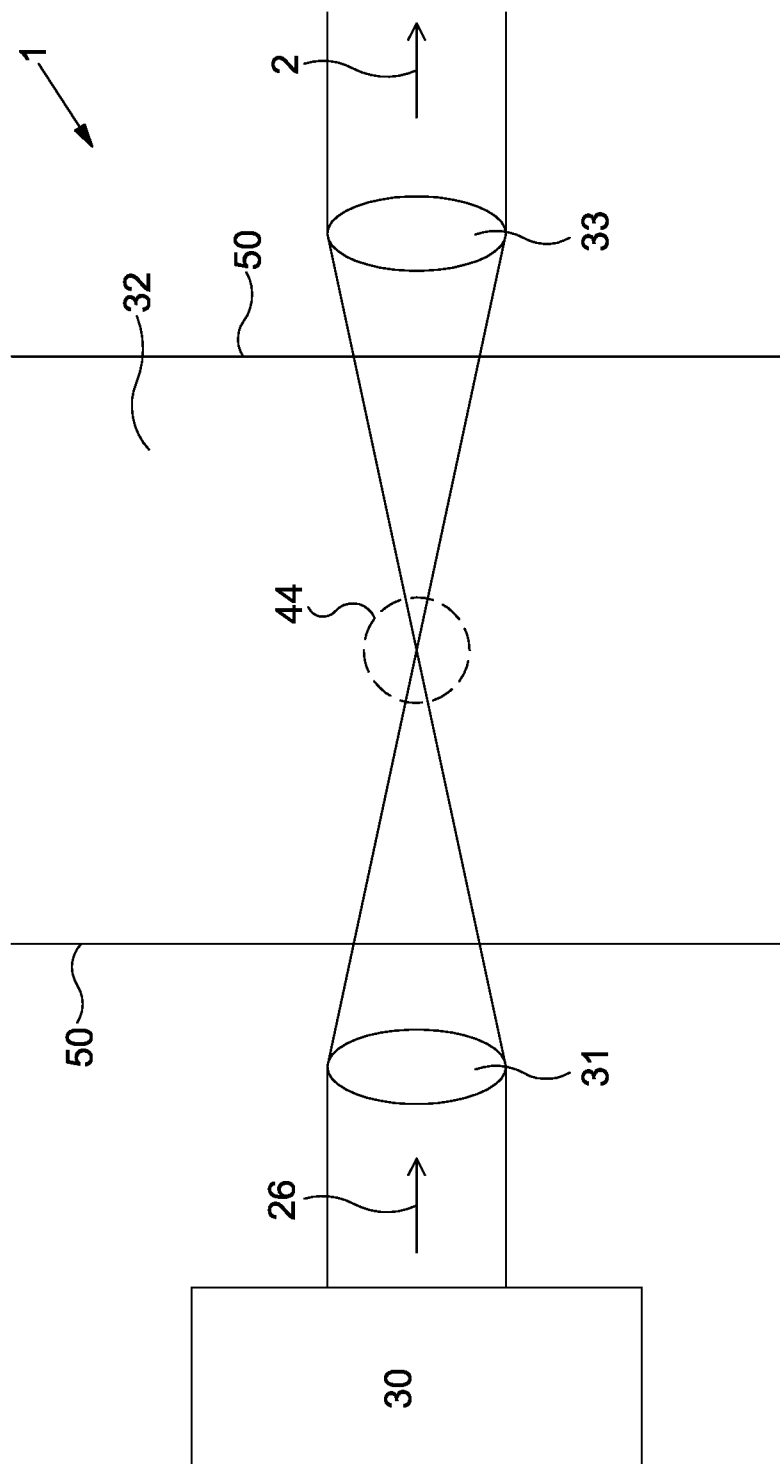


Fig. 2

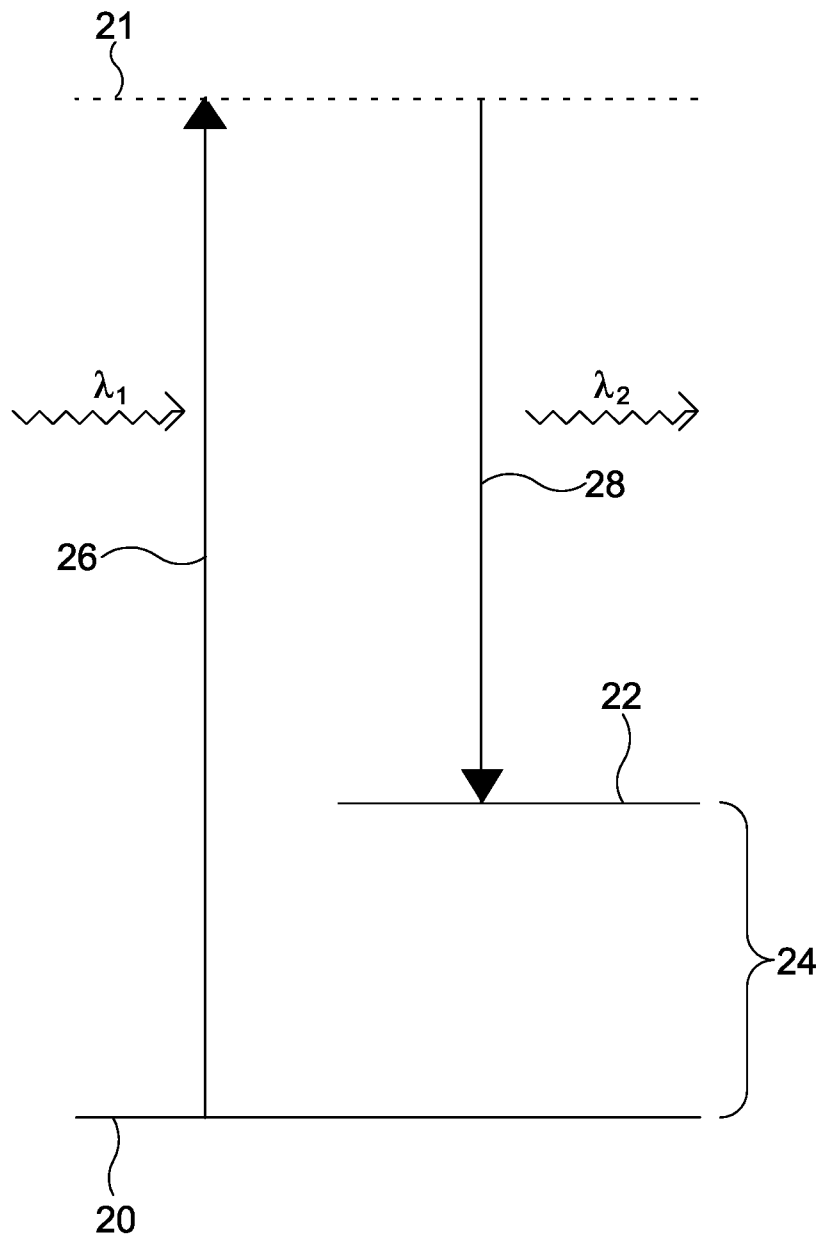


Fig. 3

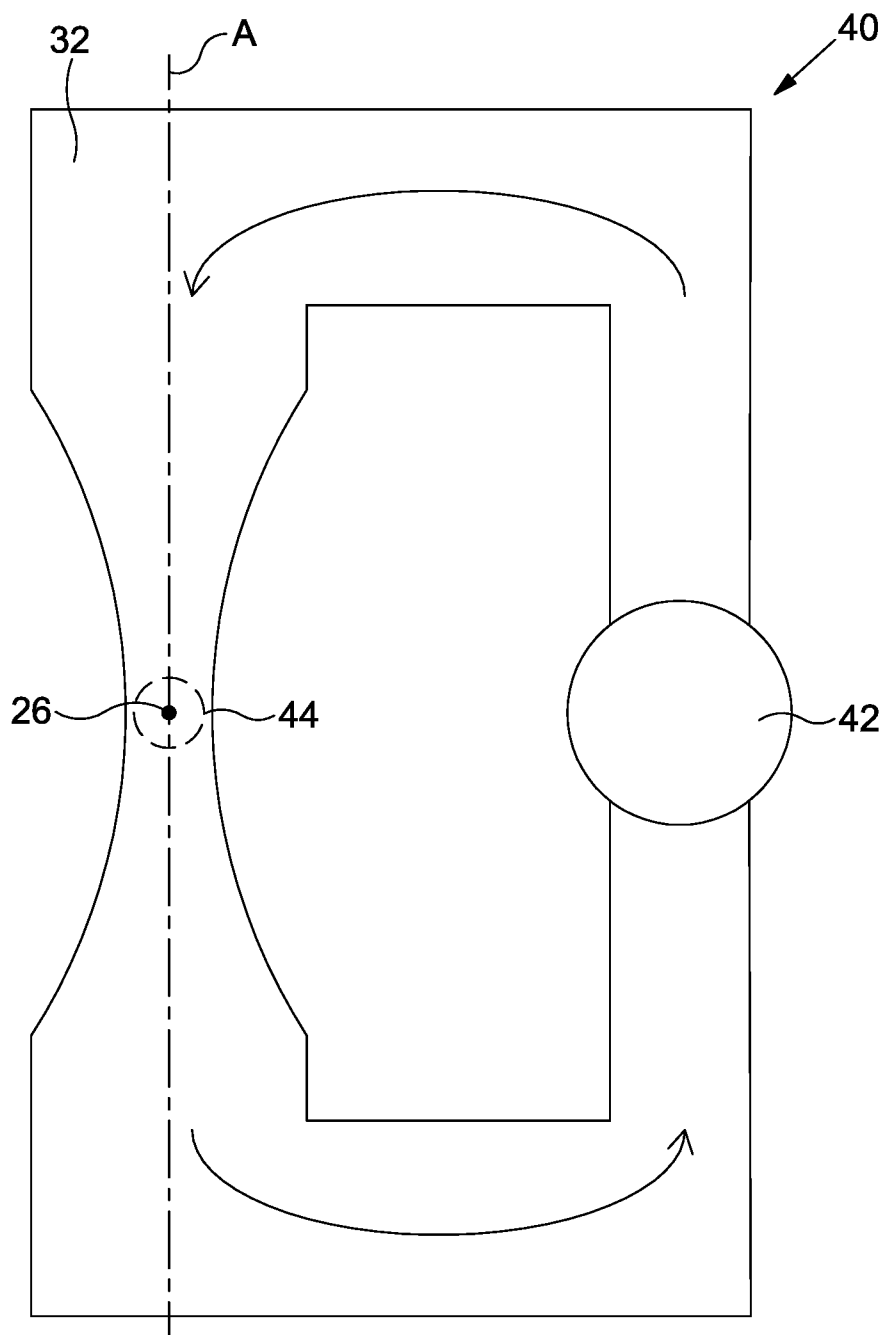


Fig. 4

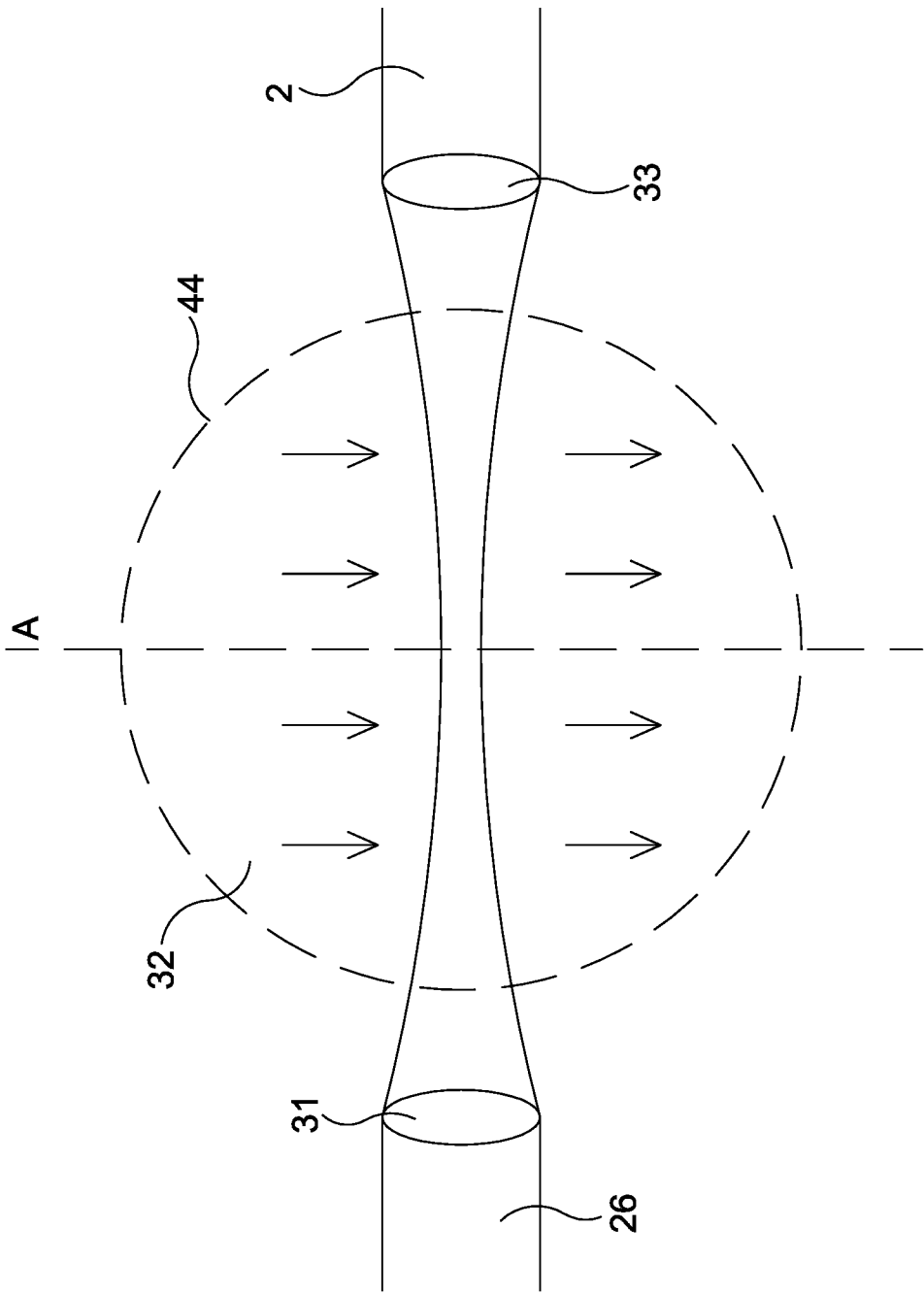


Fig. 5

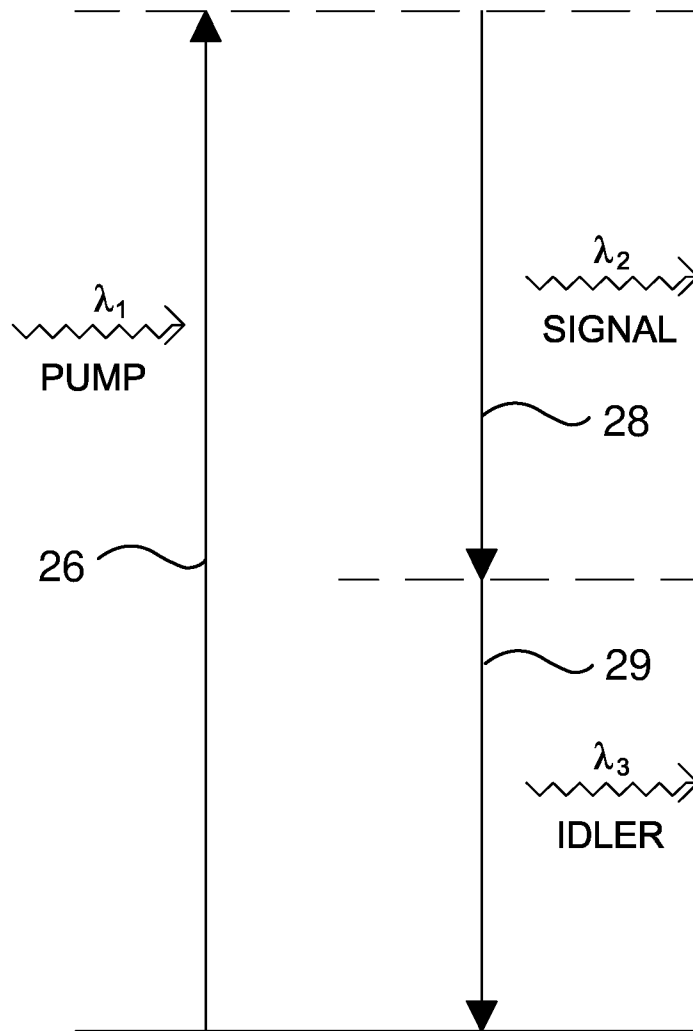


Fig. 6

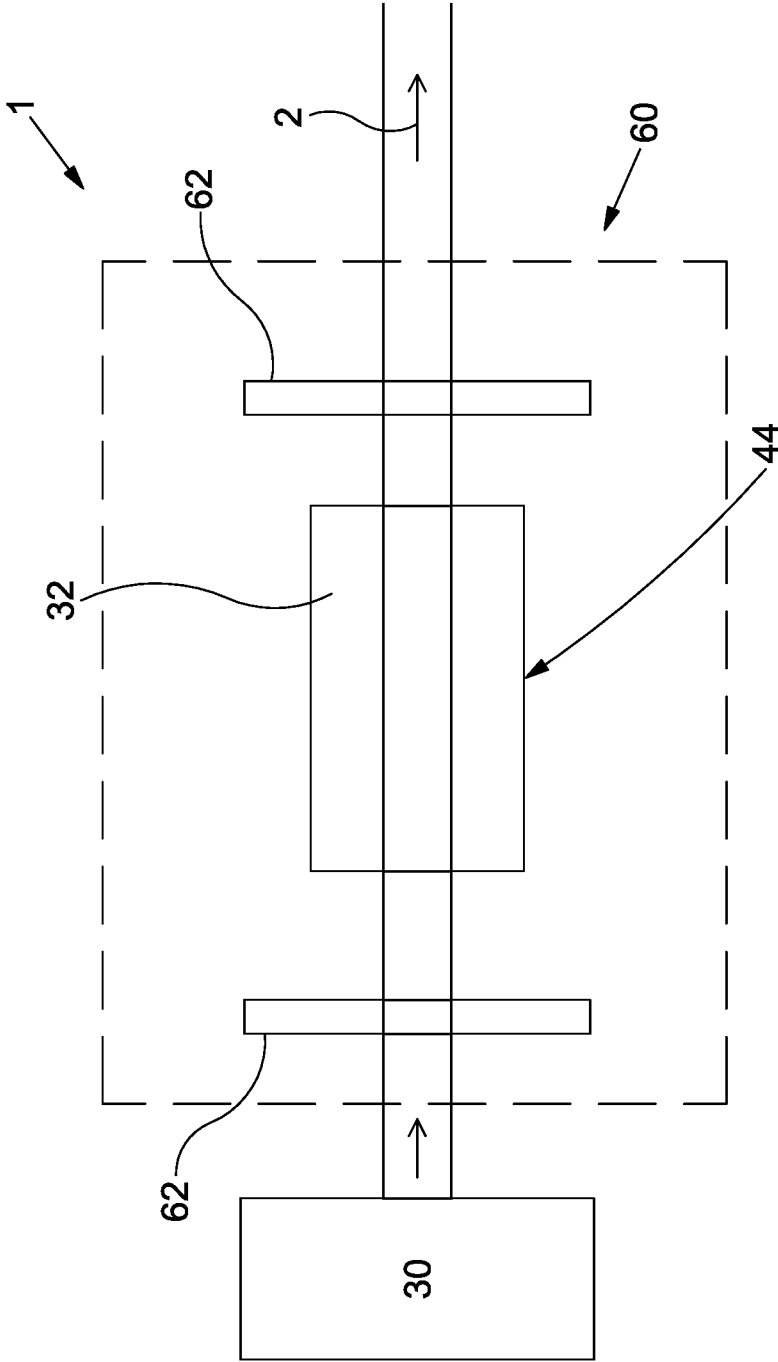


Fig. 7

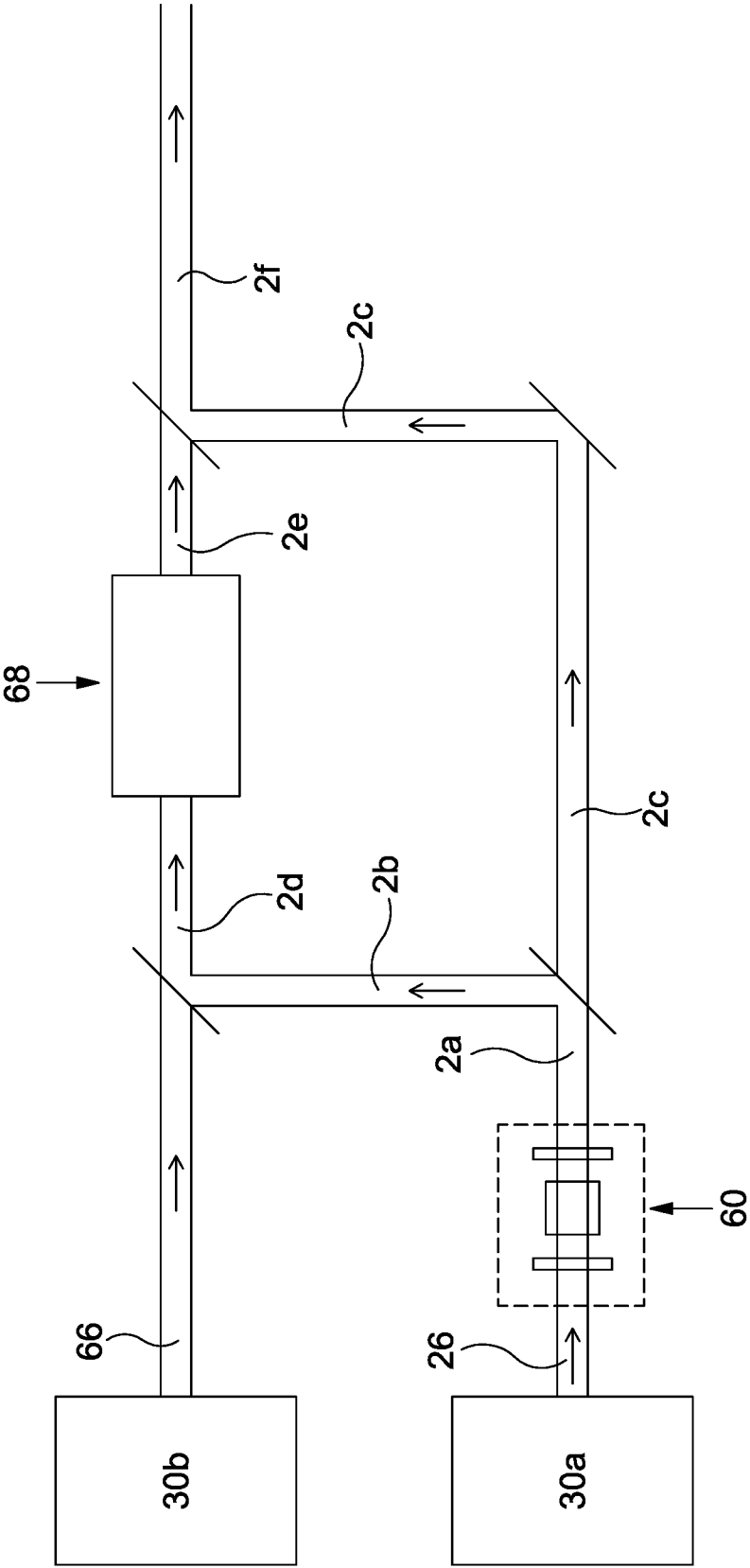


Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/086403

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 H05G2/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G03F H05G

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7 649 188 B2 (KOMATSU MFG CO LTD [JP]; GIGAPHOTON INC [JP]) 19 January 2010 (2010-01-19)	1,2,8, 19,20,26
A	column 7, line 36 - line 42; column 8, line 35 - column 6, line 6; figures	3-7, 9-18, 21-25, 27-37
A	----- EP 3 361 315 A1 (ASML NETHERLANDS BV [NL]) 15 August 2018 (2018-08-15) abstract; figures -----	1-37



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search

18 March 2020

Date of mailing of the international search report

25/03/2020

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2019/086403

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 7649188	B2	19-01-2010	JP 5100990 B2 19-12-2012
			JP 2006135298 A 25-05-2006
			US 2006078017 A1 13-04-2006
			US 2007187628 A1 16-08-2007

EP 3361315	A1	15-08-2018	CN 110291464 A 27-09-2019
			EP 3361315 A1 15-08-2018
			KR 20190113932 A 08-10-2019
			TW 201832024 A 01-09-2018
			US 2018224753 A1 09-08-2018
			WO 2018145837 A1 16-08-2018
