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(54) METHOD AND DEVICE FOR FOCUSING EUV RADIATION

(57) The present invention refers to a method for focusing extreme ultraviolet (EUV) radiation providing low transmission losses and minimal chromatic aberration.

A corresponding method comprises the steps of coupling the EUV radiation into an optical input port (A) of a gas-filled capillary discharge waveguide, GFCDW, having a rectilinear capillary (10) filled with a plasma containing free electrons forming a plasma lens for the EUV radiation, wherein the free electrons have a density profile with a minimum density in the center and a maximum density at the wall of the capillary (10); and coupling the EUV radiation transmitted through the GFCDW out of the output port (B). Further, a related focusing device is concerned.

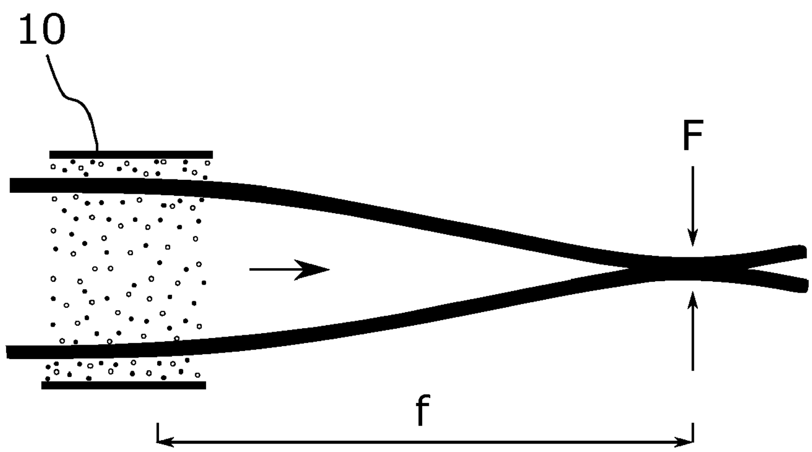


FIG. 2

EP 3 905 267 A1

Description

[0001] The present invention refers to a method for focusing extreme ultraviolet (EUV) radiation providing low transmission losses and minimal chromatic aberration. Further, a related focusing device is concerned.

Technological Background

[0002] EUV (or XUV) radiation is the part of the electromagnetic spectrum at wavelengths between 10 nm and 124 nm (corresponding to photon energies between 10 eV and 124 eV). This radiation has important applications in science and industry, including EUV lithography, coherent diffractive imaging, and attosecond science. EUV lithography enables the fabrication of smaller and faster integrated circuits compared to conventional lithography techniques and therefore plays a crucial role in the future development of information technologies. Usually a wavelength of 13.5 nm (corresponding to a photon energy of 90 eV) is used due to the availability of highly reflective multilayer mirrors. Coherent diffractive imaging using intense EUV pulses has enabled the in-situ imaging of nanostructured objects on a femtosecond timescale. Finally, the generation of attosecond EUV pulses provides tools to measure dynamic processes on the attosecond timescale. Examples include the direct measurement of the Auger decay time in atoms, the dissociative ionization of H_2 molecules, and the absolute timing of the photoelectric effect with attosecond resolution. For the numerous applications, a large number of EUV radiation sources are available that include both large-scale facilities such as synchrotrons and free-electron lasers (FEL), and laboratory-scale sources such as high-harmonic generation (HHG), soft X-ray lasers and plasma sources.

[0003] For the applications mentioned above, it is crucial to be able to focus the EUV radiation to very small spot sizes. This is currently achieved by reflective mirrors or diffractive Fresnel zone plates. A disadvantage of these optical elements is that for EUV radiation the transmission losses can be very high. In addition, Fresnel zone plates exhibit high chromatic aberration, meaning that they are not suitable for focusing EUV radiation with attosecond pulse durations due to the involved pulse stretching.

[0004] In other common wavelength regimes, refractive lenses are widely used to focus, collimate or (de-)magnify electromagnetic radiation. This includes the visible, ultraviolet, infrared and terahertz regimes as well as hard X-ray radiation. Refractive lenses have not been available for EUV radiation until recently, which can be explained by the fact that EUV radiation is strongly absorbed by matter. The first refractive prism and the first refractive lens for EUV radiation were disclosed in L. Drescher et al., Nature 564, 91 (2018). In order to reduce the absorption of EUV radiation, the lenses are formed by a jet of neutral atoms instead of solids.

[0005] Such gas-phase lenses can be used at photon energies that range up to the ionization potentials of the atoms. In helium, these lenses can thus be used up to photon energies of 24.6 eV. However, this only allows focusing EUV radiation with long wavelengths (51 nm to 124 nm). Since the concept relies on the strong refraction that one encounters close to atomic resonances, these lenses are also associated with high chromatic aberration and large dispersion. Consequently, these lenses are not suitable for focusing attosecond pulses.

[0006] WO 2006/127147 A2 concerns a compact, high repetition rate, extreme ultraviolet (EUV) / soft x-ray laser and a method for generating such radiation. Excitation of a gaseous or vaporous lasing medium is achieved by discharging energy stored in a solid dielectric capacitive device through a capillary channel containing the medium. Other such capillary discharge sources, also known as gas-filled capillary discharge waveguides (GFCDW), are described in D. J. Spence et a/., J. Opt. Soc. Am. B 20, 138 (2003) and N. A Bobrova et al., Phys. Rev. E 65, 016407 (2002).

[0007] The objective problem of the invention is related to the problem of focusing pulsed EUV radiation with extremely short pulse durations in the range of hundreds of attoseconds or even below. Therefore, a method and a related device are required, which provide transmission properties with low losses and minimal chromatic aberration and dispersion within the entire spectral range of a typical attosecond EUV pulse.

Summary of Invention

[0008] The invention solves the objective problem by providing a method for focusing EUV radiation as defined in claim 1 and a varifocal EUV radiation focusing device as defined in claim 7.

[0009] The proposed method for focusing EUV radiation comprising the steps of coupling the EUV radiation into an optical input port of a gas-filled capillary discharge waveguide (GFCDW) having a rectilinear capillary filled with a plasma containing free electrons forming a plasma lens for the EUV radiation, wherein the free electrons have a density profile with a minimum density in the center and a maximum density at the wall of the capillary; and coupling the EUV radiation transmitted through the GFCDW out of an optical output port.

[0010] GFCDW provide the required density profile of the free electrons, which shows a minimum of the density at the center of the waveguide, and which are thus suitable for EUV focusing applications. Such sources are described, for example, in D. J. Spence et al., J. Opt. Soc. Am. B 20, 138 (2003) and N. A Bobrova et a/., Phys. Rev. E 65, 016407 (2002), wherein the latter concerns the analysis of the discharge dynamics of hydrogen-filled capillary discharge waveguides. Further, a very high degree of ionization has been demonstrated in such sources, thereby minimizing the absorption of EUV radiation, which give rise to low transmission losses. The design of a typical GFCDW is explained in detail in the description to Fig. 3, however, the invention is not limited to such specific designs. Any gas-filled capillary discharge waveguide source which provides the claimed density profile of the free electrons may be used for focusing EUV radiation according to the invention.

[0011] Nevertheless, for the given GFCDW designs preferred geometric parameters can be defined. In particular, a capillary length between 0.5 cm and 10 cm and a diameter between 0.2 mm and 2 mm, more preferably between 0.4 mm and 2 mm and even more preferably between 1 mm and 2 mm, are preferred to realize practically relevant focal lengths between 0.05 m and 1 m within the entire EUV energy range. For a hydrogen plasma, a typical density of free electrons is $4.5.10^{18}$ cm^{-3} at the center and 7.10^{18} cm^{-3} at the wall of the capillary.

[0012] An optical input port is an element or region which is used to couple EUV radiation into the capillary of the GFCDW. In particular, the optical input port can be one end of the capillary. An optical output port is an element or region which is used to again couple the focused EUV radiation out of the capillary of the GFCDW. In particular, the optical output port can be the other end of the capillary.

[0013] The gas inside the capillary has to be ionized to become a plasma in which free electrons can interact with the EUV radiation propagating through the capillary. This interaction gives rise to a refractive index for the transmission of EUV radiation through the free electron plasma. The proposed density profile of the free electrons then results in a corresponding radial refractive index profile over the cross-section of the capillary. Therefore, the density profile of the free electrons in the plasma defines the focusing properties of the resulting plasma lens.

[0014] Preferably, the density profile of the free electrons is a continuous radial symmetric function of the radius of the capillary. For focusing applications, it is particularly preferred that the free electrons of the plasma in the capillary have a parabolic (or nearly parabolic) density profile. The resulting radial refractive index profile is than comparable to the refractive index profile in a standard gradient-index (GRIN) lens.

[0015] The invention is entirely based on refraction due to free electrons in the plasma, while refraction due to ions can almost always be neglected. The refractive index η due to free electrons in a plasma is given by:

$$\eta = \left(1 - \omega_p^2/\omega_0^2\right)^{1/2},\ \omega_p^2 = n_e e^2/\varepsilon_e m_e.$$

[0016] Here ω_p is the plasma frequency, ω_0 is the central frequency of the electromagnetic EUV radiation, n_e is the density of free electrons, ε_0 is the vacuum permittivity, m_e is the electron mass, and e is the elementary charge. As it can be seen from the equation, the contribution from the free electrons to the refractive index *n* is always positive but below unity.

[0017] In order to be able to exploit the refraction due to free electrons in a plasma for focusing applications, a preferably parabolic radial profile of the plasma density is required, i.e., the plasma density needs to be smaller in the "center" of the lens as compared to their "edges". Such a profile can be achieved by using a GFCDW that generates a plasma column with the required density properties of free electrons. In other words, the local refractive index in the plasma inversely depends on the local density of the free electrons in the plasma, which means that plasma regions with a high density of free electrons have a lower refractive index than regions with a lower density of free electrons. A parabolic density profile of free electrons in the plasma results in forming a GRIN-type lens along the axis of the capillary in which the refractive index in the plasma gradually decreases from the center to the wall of the capillary.

[0018] The present invention is thus based on the use of an externally generated plasma with a specific inhomogeneous density profile of free electrons for focusing EUV radiation. The use of a plasma for focusing EUV radiation instead of a solid or gas has several advantages:

(1) Since plasma only consists of ions and electrons, absorption of EUV radiation is strongly reduced due to a reduced light-matter interaction.

(2) By exploiting the refraction due to free electrons, chromatic aberration is strongly reduced due to their widely frequency independent response and the lack of electronic resonances.

(3) In comparison to a solid lens, the plasma is constantly replenished. As a consequence, there are no problems caused by a damaging the lens material.

(4) The linear geometry of the plasma lens allows a flexible use for applications. In comparison to a reflective mirror, a plasma lens does not deflect the EUV beam but performs focusing during transmission.

[0019] Therefore, the present invention allows focusing EUV radiation within their entire photon energy range (10 eV to 124 eV). Furthermore, focusing of EUV pulses with attosecond pulse durations is also possible because the high transmission bandwidth of a plasma lens allows focusing with minimal chromatic aberration.

[0020] Preferably, the plasma is generated by ionizing hydrogen molecules (H_2). However, other atomic or molecular gases, such as oxygen (O_2), nitrogen (N_2), or dichloride (Cl_2), can also be used alone or in combination with one another. Preferably, the capillary material comprises alumina (Al_2O_3). Other preferred materials which can be comprised by the capillary are graphite, beryllia (beryllium oxide, BeO), metals (e.g. tungsten), fused silica or further ceramics. In particular, the capillary of the GFCDW could be a tube made of one or more of said materials. Most preferably, an alumina (Al_2O_3), beryllia (BeO), tungsten, or graphite tube is used. The material of the tube should be able to withstand the discharge conditions without significant erosion.

[0021] Preferably, the gas is fully ionized at the wall of the capillary. Under this condition, a maximum in the electron density can be reached with lowest possible ion density for a specific gas. Having a low ion density helps to reduce transmission losses and minimizes optical distortions during focusing. In the center of the capillary, the degree of ionization may be lower due to the required density profile of the free electrons.

[0022] Preferably, the focal length f of the plasma lens is changed by modifying the density of the plasma. Modifying the density of the plasma also modifies the density of the free electrons in the plasma, which also influences the refractive index profile of the plasma lens. In particular, the focal length f of the plasma lens can be changed in-situ by actively controlling the density of the plasma. With this method, a varifocal EUV radiation focusing device can be realized, which enables adaptive optics to be applied to EUV applications. Another advantage of a variable focus length is the ability of focusing EUV radiation even at very different photon energies (corresponding to different wavelengths) to the same focal plane. This may be of particular interest for the development of detectors for the EUV range.

[0023] In another aspect, the present invention provides a varifocal EUV radiation focusing device, comprising a GFCDW configured for focusing EUV radiation by a method according to the invention, and a control means configured to in-situ control the density of the plasma in the GFCDW. By controlling the plasma density, the focal length *f* of the plasma lens can be changed. A varifocal EUV radiation focusing device is a plasma lens with variable focal length.

[0024] The corresponding control means is adapted to control the density of the plasma, which can, for example, be a control over the gas flow (gas pressure) and / or the degree of ionization in the gas as control parameters. The control means can, for example, comprise a valve and / or a controller for changing the respective control parameters. Further, the control means can comprise a control unit adapted to regulate the valve and / or the controller for changing the respective control parameters as required for an application. A varifocal EUV radiation focusing device of the present invention is in particular interesting for controlling the depth of focus in attosecond EUV imaging and microscopy applications.

[0025] The present invention is further related to the use of a method according to the invention in EUV lithography. Further, the use of a method according to the invention for coherent diffractive imaging is concerned. In yet another aspect, the present invention claims the use of a method according to the invention for focusing EUV attosecond pulses.

[0026] Further preferred embodiments of the invention result from features mentioned in the dependent claims.

[0027] The various embodiments of the invention mentioned in this application can be combined with each other to advantage, unless otherwise specified in the particular case.

Brief Description of the Drawings

[0028] In the following, the invention will be described in further detail by figures. The examples given are adapted to describe the invention. The figures show:

Fig. 1 a schematic diagram of a GFCDW that can be used for focusing EUV radiation;

Fig. 2 a schematic of the principle of focusing an EUV beam by a method according to the invention;

Fig. 3 a simulation of the focusing of an EUV beam by a method according to the invention; and

Fig. 4 a simulation of the duration of an attosecond EUV pulse after focusing by a method according to the invention.

Detailed Description of the Invention

[0029] Fig. 1 shows a schematic diagram of an exemplary GFCDW that can be used for focusing EUV radiation. The design is based on a prior art GFCDW disclosed in D. J. Spence et a/., J. Opt. Soc. Am. B 20, 138 (2003). The discharge is double-ended, which allows for an improved shielding of the high-voltage cathode electrode 12. The capillary 10 may be, for example, an alumina tube with an inner diameter of 400 μm and an outer diameter of 1 mm. The high-voltage cathode electrode 12 is located at the center of the longitudinal axis of the capillary 10, while near to both ends of the capillary 10 gas injection slots 22 are provided to allow the introduction of an atomic or molecular gas 20 into the capillary 10 for plasma generation. The ends of the capillary 10 are open to a surrounding vacuum chamber such that the introduced gas can freely flow out of the capillary 10 at both ends. Thereby, a uniform steady-state pressure in the region of the capillary between the gas injection slots 22 can be established. Earth electrodes 14 are located on both ends of the capillary 10. The electrodes 14 and the capillary 10 may be surrounded by a dielectric housing 16 (e.g. a plastic housing) which is held within an earthed metallic containment 18 (e.g. an aluminum can) for shielding. For plasma generation, a high voltage is applied between the cathode electrode 12, which is connected to a high voltage lead, and the two earth electrodes 14.

[0030] An EUV beam can be coupled into the gas plasma inside the capillary 10 via an optical input port A on one end of the capillary 10. The outcoupling of the focused EUV beam can then be done via an optical output port B located at the other end of the capillary 10. Between both ends of the capillary 10, the EUV beam is guided along the longitudinal axis of the capillary 10. That means that a collimated EUV beam can be coupled into the capillary waveguide at one end of the capillary 10, which is then internally guided to the other end of the capillary 10. Finally, the EUV beam is again coupled out of the capillary 10. During the transmission through the capillary waveguide, the phase fronts of the EUV beam become modified in relation to the density profile of the free electrons in the plasma. This leads to focusing the EUV beam behind the capillary 10.

[0031] Fig. 2 shows a schematic of the principle of focusing an EUV beam by a method according to the invention. The density of free electrons (dots) in the capillary 10 of the GFCDW has a radial profile, which shows a maximum density near the walls of the capillary and wherein the density constantly decreases in the direction towards the center of the capillary. However, the distribution of the ions (circles) can be assumed to be homogeneous. An EUV beam (the lateral extend is represented by two lines) propagates from left to right and becomes focused in the focal point F due to the interaction with the free electrons in the plasma. The focal length *f* of the resulting plasma lens, which can be defined in accordance to the focal length f of a standard GRIN lens, can be simply changed by modifying the density of the plasma, in particular the density of free electrons in the plasma. The modification can be performed, for example, by regulating the gas flow (gas pressure) and/or the degree of ionization inside the capillary 10.

[0032] Fig. 3 shows a simulation of the focusing of an EUV beam by a method according to the invention. An input EUV pulse at a central photon energy of 80 eV with a full width at half maximum (FWHM) bandwidth of 23.5 eV was assumed. For the plasma, hydrogen was used as gas, which was fully ionized inside the capillary. The simulation shows the spatial-spectral distribution of the focused EUV beam achieved by a GFCDW with a capillary having a length of 5 cm and a diameter of 0.3 mm, wherein a parabolic density profile along the radial direction was assumed for the free electrons with a maximum electron density of $7\cdot10^{18}$ cm^{-3} at the wall of the capillary and a minimum electron density of $4.5\cdot10^{18}$ cm^{-3} at the center of the capillary. From this simulation parameters, a focal length f of the plasma lens of 84 cm could be derived. A minimum focus size of 40 μm can be achieved, which only weakly depends on the photon energy owing to low chromatic aberration. The simulation shows the feasibility of using a GFCDW as a plasma lens for focusing EUV beams at higher photon energies than those that could previously by focused with gas-phase lenses.

[0033] Fig. 4 shows a simulation of the duration of an attosecond EUV pulse after focusing by a method according to the invention. The simulation was based on the same parameters as they were used in the simulation described in the description to Fig. 3. The simulation shows that a Fourier-limited EUV pulse at 80 eV and with a duration of 103 as experiences only a moderate stretching to 126 as. It can be seen that a focusing method according to the invention offers very favorable dispersive properties for attosecond physics, which is allowing the focusing of attosecond pulses and maintaining an attosecond pulse duration in the focus.

Reference List

[0034]

10	capillary
12	cathode electrode
14	earth electrode
16	housing
18	earthed containment
20	gas (e.g. hydrogen)
22	gas injection slots
A	optical input port
B	optical output port

Claims

1. Method for focusing extreme ultraviolet, EUV, radiation, comprising the steps of:

   - coupling the EUV radiation into an optical input port (A) of a gas-filled capillary discharge waveguide, GFCDW, having a rectilinear capillary (10) filled with a plasma containing free electrons forming a plasma lens for the EUV radiation, wherein the free electrons have a density profile with a minimum density in the center and a maximum density at the wall of the capillary (10); and
   - coupling the EUV radiation transmitted through the GFCDW out of an optical output port (B).

2. Method according to claim 1, wherein the free electrons of the plasma in the capillary (10) have a parabolic density profile.

3. Method according to claim 1 or 2, wherein the plasma is generated by ionizing hydrogen molecules.

4. Method according to one the preceding claims, wherein the capillary (10) material comprises alumina.

5. Method according to one the preceding claims, wherein the gas is fully ionized at the wall of the capillary (10).

6. Method according to one the preceding claims, wherein focal length f of the plasma lens is changed by modifying the density of the plasma.

7. Varifocal EUV radiation focusing device, comprising a GFCDW configured for focusing EUV radiation by a method according to one the preceding claims, and a control means configured to in-situ control the density of the plasma in the GFCDW.

8. Use of a method according to one claims 1 to 6 in EUV lithography.

9. Use of a method according to one claims 1 to 6 for coherent diffractive imaging.

10. Use of a method according to one of claims 1 to 6 for focusing EUV attosecond pulses.

Amended claims in accordance with Rule 137(2) EPC.

1. Method for focusing extreme ultraviolet, EUV, radiation, comprising the steps of:

- coupling the EUV radiation into an optical input port (A) of a gas-filled capillary discharge waveguide, GFCDW, having a rectilinear capillary (10) filled with a plasma containing free electrons forming a plasma lens for the EUV radiation, wherein the free electrons have a density profile with a minimum density in the center and a maximum density at the wall of the capillary (10); and
- coupling the EUV radiation transmitted through the GFCDW out of an optical output port (B).

2. Method according to claim 1, wherein the free electrons of the plasma in the capillary (10) have a parabolic density profile.

3. Method according to claim 1 or 2, wherein the plasma is generated by ionizing hydrogen molecules.

4. Method according to one of the preceding claims, wherein the capillary (10) material comprises alumina.

5. Method according to one of the preceding claims, wherein the gas is fully ionized at the wall of the capillary (10).

6. Method according to one of the preceding claims, wherein focal length f of the plasma lens is changed by modifying the density of the plasma.

7. Varifocal EUV radiation focusing device, comprising a GFCDW configured for focusing EUV radiation by a method according to one of the preceding claims, and a control means configured to in-situ control the density of the plasma in the GFCDW, wherein the capillary (10) has a length between 0.5 cm and 10 cm and a diameter between 0.4 mm and 2 mm.

8. Use of a method according to one of claims 1 to 6 in EUV lithography.

9. Use of a method according to one of claims 1 to 6 for coherent diffractive imaging.

10. Use of a method according to one of claims 1 to 6 for focusing EUV attosecond pulses.

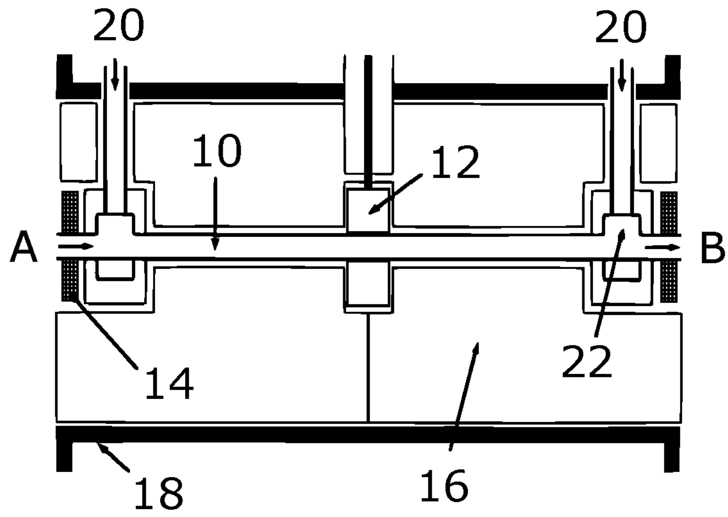


FIG. 1

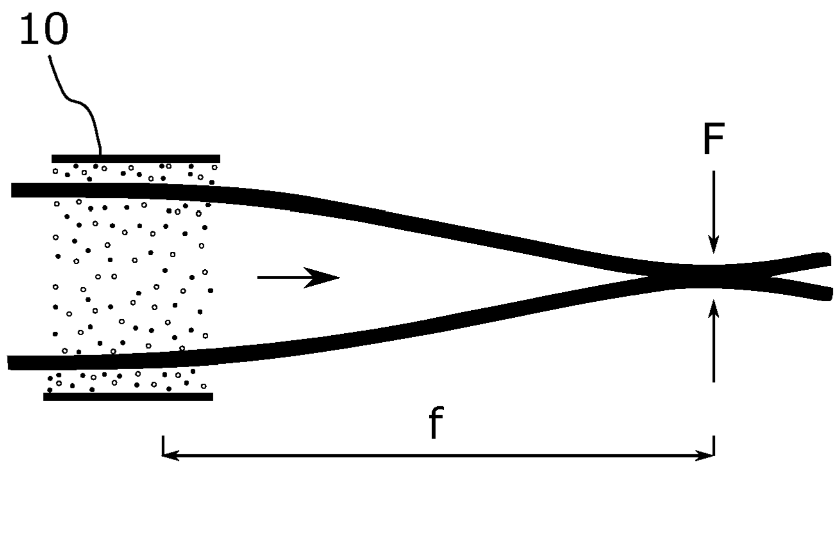
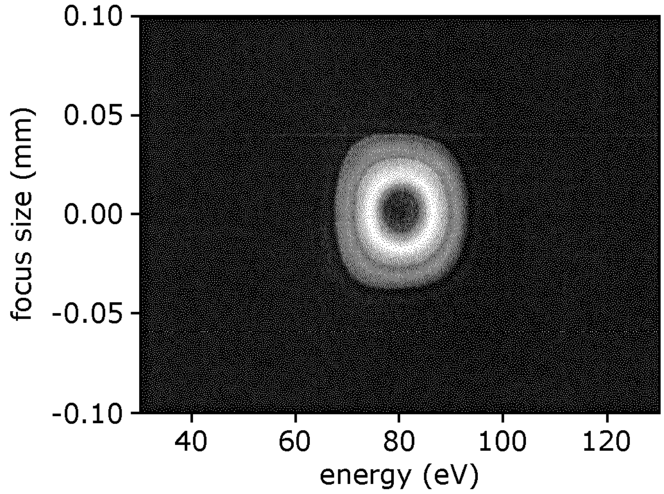


FIG. 2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-0.05
-0.10
focus size (mm)
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60
80
100
120
energy (eV)

FIG. 3

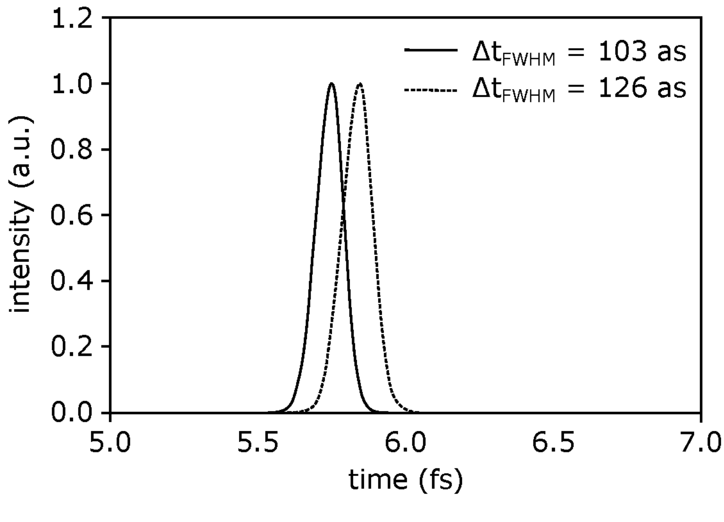
1.2
1.0
0.8
0.6
0.4
0.2
0.0
intensity (a.u.)
5.0
5.5
6.0
6.5
7.0
time (fs)
Δt FWHM = 103 as
Δt FWHM = 126 as

FIG. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 20 17 2483

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	D. J. SPENCE ET AL: "Gas-filled capillary discharge waveguides", JOURNAL OF THE OPTICAL SOCIETY OF AMERICA - B., vol. 20, no. 1, 1 January 2003 (2003-01-01), pages 138-151, XP055735947, US ISSN: 0740-3224, DOI: 10.1364/JOSAB.20.000138	7	INV. G21K1/06
A	* the whole document * -----	1-6,8-10	
A	LORENZ DRESCHER ET AL: "Extreme-ultraviolet refractive optics", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 24 April 2018 (2018-04-24), XP081137337, DOI: 10.1038/S41586-018-0737-3 * the whole document * -----	1-10	
A	DE 10 2011 007828 A1 (ZEISS CARL SMT GMBH [DE]) 19 April 2012 (2012-04-19) -----	1-10	TECHNICAL FIELDS SEARCHED (IPC): G21K

1 The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	7 October 2020	Giovanardi, Chiara

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DE 102011007828 A1	19-04-2012	NONE	

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