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The invention concerns an optical device for controlling a light beam comprising:

- a beam shaping unit for increasing the uniformity of the spatial intensity profile of the light beam;
- a lens system; and
- a focusing unit.

Such systems are known for providing a focused light beam with an increased spatial intensity profile uniformity. For a wide range of laser applications in industry, medicine, biology, physics, chemistry as well as interdisciplinary fields such as biotechnology, biophotonics, optomechanics, or even mechatronics, a usually coherent or semi-coherent beam with specific optical characteristics and a specific spatial profile is required.

Despite many methods generating a highly focused beam used in communications, medical surgery, micromachining, material processing, and welding, there still are various challenging knots in achieving isotropic volumetric results. This even becomes more pronounced when a plane of uniform light is required as by increasing the dimensions of the plane the beam width expands rapidly compared to the plane of focus. In applications such as rapid annihilation of nano-organism and microorganism using high-frequency light, pollution analysis in microbiology and oceanography, high-resolution light-sheet fluorescence microscopy, wound healing in immunocompromised patients like diabetics, cancer, and transplants patients, there is a need for a sheet of light with minimum width, minimum divergence, and uniform intensity distribution along all axes to obtain the optimum results from the process.

In most commercial techniques that require a highly focused beam, a laser (solely or in combination with some optical elements) emitting a highly narrow beam with either Gaussian, super-Gaussian, or a sort of Bessel beam intensity profile is utilized. However, many undesired optical effects exist that undermine the quality of the process. For example, for clean-cutting or precise welding using the focused laser beams of these distributions, the existence of the side-shoulders around the central peak at the focal plane would substantially degrade the quality of the work. Replacing refractive lenses with diffractive optical elements (DOE) is an alternative approach, however, the optical diffraction efficiency, parasitic diffraction orders, and high costs are among the disadvantages of using DOEs solely.

It is an object of the present invention to alleviate or resolve one or more of the disadvantages in the prior art. In particular, it is an object of the present invention to provide an optical device for controlling a light beam which provides a focused light beam of improved optical characteristics, in particular with improved uniformity along one or all axes, reduced side-shoulders, reduced width, reduced divergence, a longer working distance, a higher focusing efficiency, a lower numerical aperture and/or an extended depth of the produced light field.

This is achieved by an optical device as mentioned in the outset, wherein the lens system comprises a first lens and a second lens, wherein each of the first lens and the second lens comprises a stepped optical surface formed by active sections and reset sections alternating with each other, wherein the active sections stepwise form a surface profile, which is aspheric, wherein the stepped optical surface of the first lens faces the stepped optical surface of the second lens.

The first lens and the second lens are Fresnel or Fresnel-like lenses, but with an aspheric surface profile. A Fresnel lens has the advantage of being able to be fabricated on thin, lightweight substrates while maintaining high diffraction-efficiency and excellent optical quality. The first and second lens control the refraction phenomenon in stepwise discontinuities. Thus, the Rayleigh range (the area wherein the beam width increases by a factor of $\sqrt{(2)}$) is extended beyond the value provided by conventional systems. The optical device allows a focusing into either a highly focused spot or to a very thin sheet of light. Also, the working distance is increased and the side-shoulders in the spatial intensity profile can be reduced. Furthermore, the predictability of the beam distribution is improved. Additionally, the use of aspheric surface profiles allows forming a distortion-free image with less aberration compared to spherical or cylindrical lenses. Further, two aspheric lenses facing each other can convert a Gaussian beam into a beam with uniform intensity distribution. Therein, the intensity distribution is reshaped by the first (aspheric) lens and the second (aspheric) lens corrects the phase.

The optical device is in particular for focusing the light beam to a spot (in particular substantially on a point) or a sheet of light (in particular substantially on a line). Therefore, the elements of the optical device, in particular, the beam shaping unit, the first lens, the second lens, and/or the focusing unit, are in particular rotational symmetrical or cylindrical symmetrical (i.e. reflectional symmetry about a plane). The focusing unit is in particular for focusing the light beam on a spot or a sheet, in particular substantially a line. The optical device is in particular for controlling a coherent light beam (e.g. a laser beam) or a semi-coherent light beam (e.g. emitted by optically altered ultraviolet-visible LED modules equipped with a small lens, heat sink, power supply, cooling fan, and power cord emitting parallel intensive light). The first lens and/or the second lens may (respectively) comprise a plane optical surface opposite the stepped optical surface. The first lens is in particular a complex optical conic-aspheric-Fresnel element. The second lens is in particular a complex optical conic-aspheric-Fresnel element.

The active sections of the first lens and the second lens are curved and the reset section of the first lens and the second lens are planar/flat. Preferably, the reset sections reset the optical surface of the first and the second lens such that the sag of the optical surface is the same on the end of each active section, which end faces a symmetry axis of the respective lens. Preferably, the contact points of the active sections with the reset section on the active sections one end (with regard to a symmetry axis) are on a plane and the contact points of the active sections with the reset sections on the active sections other end (with regard to a symmetry axis) are on another plane. Preferably, the active sections and reset sections of the first and second lens form a zigzag in a cross-section through a symmetry axis of the respective lens (i.e. trace a path between two parallel lines), wherein in particular the active sections form curved lines and/or the reset sections form straight lines. Preferably, the active section and reset sections of the first lens and the second lens are ring-shaped (in particular radial/homocentric) segments, thereby focusing light on a point, or are straight/axial segments, thereby focusing light on a line. The first and the second lens may each have the form of a slab/rectangle or of a disk. The surface profile stepwise formed by the active sections of the first lens and/or the surface profile stepwise formed by the active sections of the second lens is preferably convex.

The first and/or the second lens may be a conic-aspheric-Fresnel lens. The stepped optical surface of the first and/or the second lens may have complex structures that are designed specifically using the combination of meso-aspheric optical structures and conic-structured-stepped-phase symmetrical elements. Preferably, a central part of the stepped optical surface of the first lens and the second lens, respectively, has a rotationally symmetric conic shape (thus, a focused light spot can be provided) or has a conic shape along one plane (thus, a sheet of light can be provided). In particular, there is at least one active section which borders with one reset section on its one end and with another reset section on its other end. Preferably, there are at least two, at least three, at least four or at least five active sections, wherein each of the active sections borders on its one end with one reset section and on its other end with another reset section.

In the first lens and the second lens, in particular the direction of propagation of light does not change within the medium (unless scattered), but the light only deviates in a particular direction depending on the lenses' structure providing a better focusing performance. For example, a higher rate of active and reset section (i.e. of grooves) provides better image quality.

Besides, the first and second lens provide a controllable optical system for desired phases and amplitudes, while providing a good magnification and a high amount of light collection. The rays are in particular diffracted and entrapped inside the respective lens to manipulate the phase and amplitude.

Preferably, under the uniformity of the spatial intensity profile is understood the beam uniformity (U_η) as defined in ISO 13694:2018 for cw-beams, wherein η is 0.3 and lower (i.e. closer to 0) U_η means higher beam uniformity. U_η is optionally reduced by the influence of the beam shaping unit by at least 0.01, at least 0.1 or by at least 0.2. Optionally, the beam uniformity is (additionally or alternatively) increased (and therefore U_η decreased) for η being one of 0.1, 0.2, 0.4, 0.5, 0.6 or 0.7. This measure is to be applied under the assumption that the light beam supplied to the beam shaping unit is a Gaussian beam.

The intensity distribution of the light beam at the focused area in both cases (i.e. spot or light sheet) has in particular a top-hat profile and can be approximated theoretically with a Flattened Gaussian beam (FGB) distribution, thus, no strong side-shoulder can be detected either in near-field or in far-field making it a perfect candidate for applications such as clean-cut, welding, micromachining, photonics, the annihilation of microorganism or highly precise medical surgery. The focusing efficiency of the first lens and the second lens of the lens system depends on the degree of their conical part as well as how the phase profile is fabricated. Depending on the shape of the center of the respective lens surrounded by Fresnel zones, the optical characteristics of the focused beam would be different. If the center part has a symmetrical conic shape (e.g. like an Axicon) with a fan-angle of β, then a highly focused spot could be formed. However, if the center part has a conic shape along one plane (like what we see in line-generator elements), then a sheet of light could be formed. Producing a super thin light sheet or highly focused spot has a significant impact if the Rayleigh range (the area when the beam width increases by a factor of $\sqrt{2}$) is extended beyond the value provided by the conventional standard systems. For controlling the expansion, the second lens creates an extra phase shift along the y-axis and forces an angular momentum similar to what we confront in the twisted beam preventing the beam from expansion along the propagating axis.

In an advantageous embodiment, the surface profile stepwise formed by the active sections of respectively the first lens and/or the second lens is substantially oblate elliptical in a cross-section through a symmetry axis (or symmetry plane) of the respective first lens and/or second lens. I.e., it corresponds to the oblate section of an ellipse. The symmetry axis may in particular be the optical axis.

It is preferable if the surface profile stepwise formed by the active sections of the first lens is defined by the sag z(r) in a cross-section through a symmetry axis of the surface profile, with r being the displacement from the symmetry axis of the surface profile, wherein

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16}$$

wherein

the radius of curvature R=1/c is between 2.5 and 130,
the conic constant k is between 0.005 and 3,
the absolute value of α_1 is between 0 and 0.1,
the absolute value of α_2 is between 0 and 0.1, and
the absolute value α_i is between 0 and 0.02 for (i=3,4,5,6,7,8). The symmetry axis is preferably the optical axis of the first lens. Thus, particularly good optical characteristics are achieved. Preferably, R is between 5 and 65. Preferably, k is between 0,01 and 1,5. Preferably, α_1=0,0002, α_2=0,002 and/or α_i is less than 0.01, more preferably less than 0.001, in particular 0, for (i=3,4,5,6,7,8). The first lens can comprise a material with an isotropic or anisotropic optical index. The thickness of the first lens is preferably chosen such that the absolute value of the thickness exceeds the deepest groove depth formed between active and reset sections. In particular, the first lens is between 1 and 2000 mm thick. The conic constant k is given by $k=-e^2$, where e is the eccentricity of the conic section.

Depth/-Frequency-parameter: If this parameter is positive, then it corresponds to the depth of each groove in lens units. If negative, then it corresponds to the frequency of the grooves (which corresponds to the number of reset section or the number of the active sections). For example, a value of -2.0 will yield 2 grooves per radial/axial lens unit. If the groove depth is defined, the radial positions of the grooves will generally vary; if the groove frequency is defined; the groove depth will vary. Preferably, the depth/frequency-parameter of the stepped optical surface of the first lens is between ±0.05 and ±(1/3).

Pitch-parameter (in degrees): The pitch is the angle the reset sections ("inactive" faces) (those faces nominally parallel to the symmetry axis) make concerning the symmetry axis. The pitch is generally radially outward, no matter if the pitch angle is positive or negative. The pitch-parameter of the inactive sections of the first lens is preferably between 2° and 45°.

It is advantageous if the surface profile stepwise formed by the active sections of the second lens is defined by the sag z(r) in a cross-section through a symmetry axis of the surface profile, with r being the displacement from the symmetry axis of the surface profile, wherein

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16}$$

wherein

the radius of curvature R=1/c is between 2.5 and 130,

the conic constant k is between 0.01 and 5,

the absolute value of α_1 is between 0 and 0.1,

the absolute value of α_2 is between 0 and 0.1, and

the absolute value of α_i is between 0 and 0.01 for (i=3,4,5,6,7,8). The symmetry axis is preferably the optical axis of the second lens. Thus, particularly good optical characteristics are achieved. Preferably, R is between 5 and 65. Preferably, k is between 0,02 and 3. Preferably, α_1=0,0002, α_2=0,002 and/or α_i is less than 0.01, more preferably less than 0.001, in particular 0, for (i=3,4,5,6,7,8). The first lens can comprise a material with an isotropic or anisotropic optical index. The thickness of the second lens is preferably chosen such that the absolute value of the thickness exceeds the deepest groove depth formed between active and reset sections. In particular, the second lens is between 1 and 2000 mm thick. Preferably, the depth/frequency-parameter of the stepped optical surface of the second lens is between ±0.01 and ±1. The pitch-parameter of the inactive sections of the first lens is preferably between 2° and 22.5°.

It is preferable if the first lens and the second lens are each rotation-symmetrical (around an optical axis). Thus, light is focused on a point and a spot of light is provided. In this case, the active section and the reset sections of the first lens and the second lens are in particular radial facets.

Alternatively, it is preferable if the first lens and the second lens are each a general cylindrical lens. Thus, a sheet of light can be provided for and the light is in particular focused on a line. In this case, the active sections and reset sections form in particular axial facets. Under general cylindrical is understood that the respective lens is reflectional symmetrical but at least one of its faces is the section of a generalized cylinder (i.e. the base surface of which does not need to be a circle). In particular, the surface profile formed by the active sections of the first and/or the second lens has the form of a section of a generalized cylinder.

In an advantageous embodiment, the stepped optical surface of the second lens comprises a larger number of active sections and reset sections alternating with each other per axial or radial length unit than the stepped optical surface of the first lens. At the same time, preferably, the depth of the grooves in the stepped optical surface of the second lens is preferably smaller than the depth of the grooves in the stepped optical surface of the first lens. When the number of the active and reset sections (and, therefore, the frequency of active and reset sections) is increased, and preferable at the same the depth and pitch (angle) of the slope of the grooves, in particular of the reset sections, becomes smaller, this helps the light to be guided through the focusing unit with the highest precision.

In a preferable embodiment, the second lens is placed at a distance of between 0.001 mm and 1000 mm from the first lens. Preferably, the first and second lenses are arranged such that a light beam exiting the first lens reaches the second lens without interfering with another optical element. I.e., preferably, there is provided for free-space between the first lens and the second lens.

It is preferable if the beam shaping unit is configured for converting a Gaussian beam into a flattened Gaussian beam, in particular a beam with a top-hat beam profile. Considering that most commercial lasers operate in TEM00 mode, the beam shaping unit can be used to convert a Gaussian beam into a beam with a top-hat beam profile. If we consider the light beam as a bundle of individual rays with its specific propagating vector, at each arbitrary position, according to the principle of the superposition, the superimposing of their phase and amplitude would give us the profile of the whole beam at that point. Thus, the beam shaping unit may be used to convert the Gaussian beam into a beam the distribution of which can be approximated by a Flattened-Gaussian beam, in particular with the desired mode number, controlling the uniformity of the intensity distribution and the slope of the beam profile's shoulder.

It is advantageous if the beam shaping unit comprises at least a negative lens and a positive lens, wherein optionally the negative lens and/or the positive lens are achromatic and/or aspheric. The beam shaping unit may also comprise a third lens. The negative lens of the beam shaping unit diverges the center of Gaussian beam distribution more than the tail of the distribution and the positive lens of the beam shaping unit collects them and redistributes them in a uniform shape through parallel paths. Thus, the uniformity of the light beam can be increased in a particularly efficient way. The negative and the third lens of the beam shaping unit may be cemented elements and the negative lens, optionally in combination with the third lens, may provide superior color correction and the smallest RMS spot size closest to the diffraction limit. The positive lens of the beam shaping unit may reduce wavefront errors arising from standard spherical achromats. Concerning the beam shaping unit reference is made to the paper “Gaussian to Flat-Top Intensity Distributing Lens” by David Shafer Optical Design, Inc.; 56 Drake Lane; Fairfield, Connecticut 06430; (203) 259-4929. The positive lens of the beam shaping unit is preferably a first condenser lens and the third lens of the beam shaping unit is preferably a second condenser lens. Aspheric lenses can form a distortion-free image with less aberration compared to spherical lenses. The beam shaping unit may produce a narrow elliptical beam with quasi-uniform intensity distribution. However, to use this beam, it must be transformed into a thin light sheet at the area of interest along the z-axis, which is achieved by the lens system and the focusing unit.

A positive lens is positive in at least one axis, preferably both axes. A negative lens is negative in at least one axis, preferably both axes.

It is preferable that the beam shaping unit comprises a condenser (i.e. in particular the third lens mentioned above), wherein the positive lens is arranged in the optical path of the light beam between the negative lens and the condenser lens.

It is preferable if the focusing unit comprises at least a positive lens, which is preferably aspheric and/or achromatic. The focusing unit comprises preferably at least one, more preferably at least two further lenses, which are in particular aspheric and/or achromatic. The at least one or at least two further lenses may create pre-defined distances between the bundle of rays of the light beam with phase correlation. With the positive lens of the focusing unit, the light beam is focused on the plane that is considered as the focusing plane containing a minimum width for either a light sheet or a highly focused point. Preferably, the positive lens of the focusing unit is arranged optically after the further lens(es) of the focusing unit.

In an advantageous embodiment, the optical device (in particular the lens system) comprises an aperture, in particular a soft aperture. Preferably, the aperture is arranged optically between the first lens and the second lens of the lens system.

Optionally, the lens system is arranged in the optical path of the light beam between the beam shaping unit and the focusing unit.

In a preferable embodiment, the optical device comprises a light source. The light source is optionally coherent or semi-coherent. For example, the light source may be a laser. Preferably, the beam shaping unit is arranged in the optical path of the light beam (which may be emitted by the light source) closer to the light source than the lens system and the focusing unit.

With the optical device described herein, in particular by cascading a few such optical devices, when the incident light is in the UV range, large surfaces can be disinfected rapidly with 99.9% accuracy. It is known that ultra-violet germicidal irradiation (UVGI) is a promising method but the disinfection efficacy is highly dependent on the dose (Energy/Area) and the uniformity of the light distribution along and across the area of illumination. As UV sources generally do not provide a suitable and uniform intensity distribution, exposure times as well as the shape of irradiance distribution has to be adjusted, which can be achieved with the optical device described herein. It is reported that by exposing an area with energy density doses of approximately 1 J/cm2, a 99.9% inactivation of MERS-CoV, and SARS-CoV can rapidly be achieved.

Furthermore, the optical device may be used for high-resolution 3D-imaging in light-sheet fluorescence microscopy.

By way of example, the invention is further explained with respect to some selected embodiments shown in the drawings. However, these embodiments shall not be considered limiting for the invention.

Fig. 1 schematically shows a preferred embodiment of the optical device generating a sheet of light.

Fig. 2 schematically shows the path of light rays in the optical device of Fig. 1 from different perspectives.

Fig. 3 schematically shows a preferred embodiment of the optical device generating a focused spot.

Fig. 4 schematically shows a preferred embodiment of the first or second lens.

Fig. 5a schematically shows a preferred surface profile, which is to be stepwise formed by the active sections.

Fig. 5b schematically shows another preferred surface profile, which is to be stepwise formed by the active sections.

Fig. 6a schematically shows another preferred embodiment of the optical system for providing a thin sheet of light, in the x-z-plane, illustrating the path of light rays fanned in the x-direction.

Fig. 6b schematically shows the same embodiment as Fig. 6a in the y-z-plane, illustrating the path of light rays fanned in the x-direction.

Fig. 6c schematically shows the same embodiment as Fig. 6a in the x-y-plane, illustrating the path of light rays fanned in the x-direction.

Fig. 6d schematically shows the same embodiment as Fig. 6a in the y-z-plane, illustrating the path of light rays fanned in the y-direction.

Fig. 6e schematically shows the same embodiment as Fig. 6a in the x-z-plane, illustrating the path of light rays fanned in the y-direction.

Fig. 6f schematically shows the same embodiment as Fig. 6a in the x-y-plane, illustrating the path of light rays fanned in the y-direction.

Fig. 7a schematically shows another preferred embodiment of the optical system for providing a spot of light, in the x-z-plane, illustrating the path of light rays fanned in the x-direction.

Fig. 7b schematically shows the same embodiment as Fig. 7a in the y-z-plane, illustrating the path of light rays fanned in the x-direction.

Fig. 7c schematically shows the same embodiment as Fig. 7a in the x-y-plane, illustrating the path of light rays fanned in the x-direction.

Fig. 7d schematically shows the same embodiment as Fig. 7a in the y-z-plane, illustrating the path of light rays fanned in the y-direction.

Fig. 7e schematically shows the same embodiment as Fig. 7a in the x-z-plane, illustrating the path of light rays fanned in the y-direction.

Fig. 7f schematically shows the same embodiment as Fig. 7a in the x-y-plane, illustrating the path of light rays fanned in the y-direction.

Fig. 8a schematically shows a preferred embodiment of the first lens for an optical system for focusing a light beam on a point, in a diagonal view.

Fig. 8b schematically shows the same embodiment of the first lens as Fig. 8a in the x-y-plane.

Fig. 8c schematically shows the same embodiment of the first lens as Fig. 8a in the y-z-plane.

Fig. 9a schematically shows a preferred embodiment of the second lens for an optical system for focusing a light beam on a point, in a diagonal view.

Fig. 9b schematically shows the same embodiment of the second lens as Fig. 9a in the x-y-plane.

Fig. 9c schematically shows the same embodiment of the second lens as Fig. 9a in the y-z-plane.

Fig. 10a schematically shows a preferred embodiment of the first lens for an optical system for focusing a light beam on a line, in a diagonal view.

Fig. 10b schematically shows the same embodiment of the first lens as Fig. 10a in the x-y-plane.

Fig. 10c schematically shows the same embodiment of the first lens as Fig. 10a in the x-z-plane.

Fig. 10d schematically shows the same embodiment of the first lens as Fig. 10a in the y-z-plane.

Fig. 11a schematically shows a preferred embodiment of the second lens for an optical system for focusing a light beam on a line, in a diagonal view.

Fig. 11b schematically shows the same embodiment of the second lens as Fig. 11a in the x-y-plane.

Fig. 11c schematically shows the same embodiment of the second lens as Fig. 11a in the x-z-plane.

Fig. 11d schematically shows the same embodiment of the second lens as Fig. 11a in the y-z-plane.

Fig. 12 shows a print from a software for building first or second lenses of different parameters on the left side and a lens with a different number of steps in the stepped optical surface on the right side.

Fig. 1 shows a preferred embodiment of the optical device 1 for controlling a light beam 2. The optical device 1 focuses the light beam 2 substantially on a line and produces a thin sheet of light. The optical device 1 comprises a beam shaping unit 3 for increasing the uniformity of the spatial intensity profile of the light beam 2. The optical device 1 further comprises in the path of the light beam 2 a lens system 4 and a focusing unit 5. The lens system 4 is arranged in the optical path of the light beam 2 between the beam shaping unit 3 and the focusing unit 5.

The lens system 4 comprises a first lens 6 and a second lens 7. Each of the first lens 6 and the second lens 7 comprises a stepped optical surface 8 formed by active sections 9 and reset sections 10 alternating with each other (see Fig. 4 showing the active section 9 and reset sections 10 in more detail). The active sections 9 stepwise form a surface profile 11, which is aspheric. The stepped optical surface 8 of the first lens 6 faces the stepped optical surface 8 of the second lens 7. Since the light beam 2 is to be focused on a line, the first lens 6 and the second lens 7 are each a general cylindrical lens, i.e. an aspheric cylindrical lens. Therefore, the active section 9 and reset sections 10 form axial facets of the respective first and second lens 6, 7.

The optical device 1 provides a stretched thin area of uniformity of the light beam 2 along as well as perpendicular to the propagation axis of the light beam 2, e.g. with an average thickness of 2 µm at the focus, thereby providing a thin sheet of light acting like a magic carpet. This ultra-thin sheet of light has an extended area of uniformity in the intensity distribution along all axes, which makes it an excellent candidate for many medical and industrial applications.

Fig. 2 schematically shows the paths of the light rays in the embodiment of the optical device 1 of Fig. 1 from various perspectives in more detail. In particular, the spreading of the light beam 2 to a line (along the axis of extension of the line) is visible from the image second to the top. The focusing of the light beam 2 to the line (orthogonally to the axis of extension of the line) is visible from the lower two images in Fig. 2.

Fig. 3 schematically shows another preferred embodiment of the optical device 1 for controlling a light beam 2. This embodiment differs from the embodiment shown in Fig. 1 in that the optical device 1 focuses the light beam 2 substantially on a point and produces a spot of light.

The optical device 1 comprises the beam shaping unit 3 for increasing the uniformity of the spatial intensity profile of the light beam 2. The optical device 1 further comprises in the path of the light beam 2 the lens system 4 and the focusing unit 5. The lens system 4 is arranged in the optical path of the light beam 2 between the beam shaping unit 3 and the focusing unit 5.

The lens system 4 comprises a first lens 6 and a second lens 7. Each of the first lens 6 and the second lens 7 comprises a stepped optical surface 8 formed by active sections 9 and reset sections 10 alternating with each other (see Fig. 4 showing the active section 9 and reset sections 10 in more detail). The active sections 9 stepwise form the surface profile 11, which is aspheric. The stepped optical surface 8 of the first lens 6 faces the stepped optical surface 8 of the second lens 7. Since the light beam 2 is to be focused on a point, the first lens 6 and the second lens 7 are each rotationally symmetric around their respective optical axis. Thus, the active sections 9 and the reset sections 10 form radial facets of the respective stepped optical surface 8.

The optical device 1 produces a highly focused beam with a long working distance, a low numerical aperture and an extended depth of the field. For example, by using a 488 nm laser beam of 1000 µm width with a 0.5 mrad divergence angle as an illumination source, one obtains a highly focused beam (i.e. the intensity distribution contains a sharp peak with negligible side-shoulder around the central peak) that has an average width of 1 µm over 250 µm distance along the propagation axis when it increases by $\sqrt{2}$. The optical device 1 overcomes many optical barriers existing in conventional systems for surgery, communications, micromachining, and material processing.

Fig. 4 schematically shows a section through a symmetry axis 12 of a preferred embodiment of the first lens 6 or the second lens 7 in more detail. The direction of the light beam 2 is shown as it would occur for the second lens 7 in the embodiment of Fig. 1 and Fig. 3, therefore reference is made to the second lens 7 in the following. However, it may also be used as the first lens 6. The second lens 7 comprises a stepped optical surface 8 formed by active sections 9 and reset sections 10 alternating with each other. The active sections stepwise form the surface profile 11. The form of the surface profile 11 stepwise formed is shown as a dashed line. The surface profile 11 is aspheric. In particular, the surface profile stepwise formed by the active sections 9 and the reset sections 10 of the second lens 7 is substantially oblate elliptical in a cross-section through the symmetry axis 12 of the second lens 7 (i.e. the section shown in Fig. 4). The symmetry axis 12 is the optical axis of the second lens 7.

The second lens 7 may be either rotationally symmetrical around the symmetry axis 12, e.g. for use in the optical device 1 of Fig. 3 for focusing the light beam 2 on a point, or the second lens 7 may be a general cylindrical lens, e.g. for use in the optical device 1 of Fig. 1 for focusing the light beam 2 on a line.

Fig. 5a schematically shows a preferred surface profile 11, which is to be stepwise formed by the active sections 9 of the first and/or second lens 6, 7. The surface profile 11 is aspheric.

Fig. 5b schematically shows another preferred surface profile 11, which is to be stepwise formed by the active sections 9 of the first and/or the second lens 6, 7. The surface profile 11 is aspheric and comprises a conic tip in its center.

Fig. 5a and Fig. 5b both show the surface profile 11 for a rotationally symmetric lens.

Figs. 6a to 6f schematically show another preferred embodiment of the optical system 1. In this embodiment, the optical system1 is for providing a thin sheet of light. This embodiment works similar to the one shown in Fig. 1. Therefore, in the following, only the differences between these embodiments are described. Unless stated otherwise, the features and advantages described in the context of the embodiment of Fig. 1 are also applicable in the context of the embodiment of Figs. 6a to 6f and for this reason elements that are the same or provide the same function are indicated by the same reference numerals.

In all figures, the z-axis is parallel to the optical axis of the optical device 1. Figs. 6a to 6c illustrate the path of light rays which are fanned in the direction of the x-axis and Figs. 6d to 6f illustrate the path of light rays which are fanned in the direction of the y-axis. Fig. 6a shows the x-z-plane, Fig. 6b the y-z-plane, Fig. 6c the x-y-plane, Fig. 6d the y-z-plane, Fig. 6e the x-z-plane and Fig. 6f the x-y-plane.

In this embodiment, the beam shaping unit 3 comprises a negative lens 13 and a positive lens 14, which are both achromatic and aspheric. Furthermore, the focusing unit comprises a positive lens 15 (it focuses in the y-direction), which is also achromatic and aspheric. The optical device 1 also comprises an aperture 17 between the first lens 6 and the second lens 7 and another aperture 16 after the lens system 4.

As can be seen in Fig. 6a, the light beam 2 is spread in the direction of the x-axis, which is the direction of the extension of the line that the light beam 2 is focused on. On the other hand, as can be seen in Fig. 6d, the light beam 2 is focused in the direction of the y-axis, which is the direction orthogonal to the extension of the line. Thus, a very thin sheet of light with high uniformity is provided by the optical device 1.

Figs. 7a to 7f schematically show another preferred embodiment of the optical system 1. In this embodiment, the optical system 1 is for providing a spot of light. This embodiment works similar to the one shown in Fig. 3. Therefore, in the following, only the differences between these embodiments are described. Unless stated otherwise, the features and advantages described in the context of the embodiment of Fig. 3 are also applicable in the context of the embodiment of Figs. 7a to 7f and for this reason elements that are the same or provide the same function are indicated by the same reference numerals.

In all figures, the z-axis is parallel to the optical axis of the optical device 1. Figs. 7a to 7c illustrate the path of light rays which are fanned in the direction of the x-axis and Figs. 7d to 7f illustrate the path of light rays which are fanned in the direction of the y-axis. Fig. 7a shows the x-z-plane, Fig. 7b the y-z-plane, Fig. 7c the x-y-plane, Fig. 7d the y-z-plane, Fig. 7e the x-z-plane and Fig. 7f the x-y-plane.

In this embodiment, the beam shaping unit 3 comprises a negative lens 13 and a positive lens 14, which are both achromatic and aspheric. Furthermore, the focusing unit comprises a positive lens 15 (it focuses in both the x- and the y-direction), which is also achromatic and aspheric. The optical device 1 also comprises an aperture 17 between the first lens 6 and the second lens 7 and another aperture 16 after the lens system 4.

As can be seen in Figs. 7a and 7d, the light beam 2 is focused in both the x- and the y-direction. Therefore, a highly focused spot of light is provided.

Figs. 8a to 8c show a preferred embodiment of the first lens 6 for the optical device 1 for providing a spot of light, e.g. for the embodiment of the optical device 1 of Fig. 3 or Fig. 7a. Therefore, the first lens 6 in this embodiment is rotationally symmetrical around its optical axis.

Figs. 9a to 9c show a preferred embodiment of the second lens 7 for the optical device 1 for providing a spot of light, e.g. for the embodiment of the optical device 1 of Fig. 3 or Fig. 7a. Therefore, the second lens 7 in this embodiment is rotationally symmetrical around its optical axis.

The first lens 6 of Fig. 8a and the second lens 7 of Fig. 9a are preferably used in the same optical device 1.

Figs. 10a to 10d show a preferred embodiment of the first lens 6 for the optical device 1 for providing a sheet of light, e.g. for the embodiment of the optical device 1 of Fig. 1 or Fig. 6a. Therefore, the first lens 6 in this embodiment is a general cylindrical lens.

Figs. 11a to 11d show a preferred embodiment of the second lens 7 for the optical device 1 for providing a sheet of light, e.g. for the embodiment of the optical device 1 of Fig. 1 or Fig. 6a.

Therefore, the second lens 7 in this embodiment is a general cylindrical lens. Further, Fig. 11d shows an enlarged section of the surface profile of the stepped optical surface 8.

The first lens 6 of Fig. 10a and the second lens 7 of Fig. 11a are preferably used in the same optical device 1.

Fig. 12 shows a print from a software for building first or second lenses 6, 7 of different parameters on the left side and a lens with a different number of steps in the stepped optical surface 8 on the right side.

The surface profile 11 stepwise formed by the active sections 9 of the respective lens is defined by the sag z(r) in a cross-section through a symmetry axis of the surface profile 11, with r being the displacement from the symmetry axis of the surface profile 11, wherein

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16}$$

with

the radius of curvature R=1/c,

the conic constant k,

and the quadratic terms α_i for (i=1,2,3,4,5,6,7,8), labelled Coeff r^i in Fig. 12.

In particular, the following parameters define the lens:

- The Radial Height: It is the maximum radial aperture of the lens if radially symmetric, or the y-half height if cylindrically symmetric.
- X Half-Width: This is the half-width of the lens if cylindrically symmetric. If this parameter is zero, then a rotationally symmetric lens is generated
- Thickness: The thickness of the lens should in particular be chosen in a way that the absolute value of the thickness exceeds the deepest groove depth.
- Depth/-Frequency: If this parameter is positive, then it corresponds to the depth of each groove in lens units. If negative, then it corresponds to the frequency of the grooves. For example, a value of -2.0 will yield 2 grooves per radial lens unit. If the groove depth is defined, the radial positions of the

grooves will generally vary; if the groove frequency is defined; the groove depth will vary.

- Pitch (degrees): The pitch is the angle the reset sections (i.e. “inactive” faces) (those faces nominally parallel to the local z-axis) make concerning the z-axis. The pitch is generally radially outward, no matter if the pitch angle is positive or negative.
- Radius: The base radius of curvature. This is one over the value c in the sag expression.
- The conic constant.

Patent claims:

1. Optical device (1) for controlling a light beam (2) comprising:

- a beam shaping unit (3) for increasing the uniformity of the spatial intensity profile of the light beam (2);
- a lens system (4); and
- a focusing unit (5);

characterized in that

the lens system comprises a first lens (6) and a second lens (7), wherein each of the first lens (6) and the second lens (7) comprises a stepped optical surface (8) formed by active sections (9) and reset sections (10) alternating with each other, wherein the active sections (9) stepwise form a surface profile (11), which is aspheric, wherein the stepped optical surface (8) of the first lens (6) faces the stepped optical surface (8) of the second lens (7).

2. Optical device (1) according to claim 1, characterized in that the surface profile (11) stepwise formed by the active sections (9) of respectively the first lens (6) and/or the second lens (7) is substantially oblate elliptical in a cross-section through a symmetry axis (12) of the respective first lens (6) and/or second lens (7).

3. Optical device (1) according to any one of the previous claims, characterized in that the surface profile (11) stepwise formed by the active sections (9) of the first lens (6) is defined by the sag z(r) in a cross-section through a symmetry axis (12) of the surface profile (11), with r being the displacement from the symmetry axis (12) of the surface profile (11), wherein

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16}$$

wherein

the radius of curvature R=1/c is between 2.5 and 130,
the conic constant k is between 0.005 and 3,
the absolute value of α_1 is between 0 and 0.1,
the absolute value of α_2 is between 0 and 0.1, and

the absolute value α_i is between 0 and 0.01 for (i=3,4,5,6,7,8).

4. Optical device (1) according to any one of the previous claims, characterized in that the surface profile (11) stepwise formed by the active sections (9) of the second lens (7) is defined by the sag z(r) in a cross-section through a symmetry axis (12) of the surface profile (11), with r being the displacement from the symmetry axis (12) of the surface profile (11), wherein

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16}$$

wherein

the radius of curvature R=1/c is between 2.5 and 130,
the conic constant k is between 0.01 and 5,
the absolute value of α_1 is between 0 and 0.1,
the absolute value of α_2 is between 0 and 0.1, and
the absolute value of α_i is between 0 and 0.01 for (i=3,4,5,6,7,8).

5. Optical device (1) according to any one of the previous claims, characterized in that the first lens (6) and the second lens (7) are each rotation-symmetrical.

6. Optical device (1) according to any one of claims 1 to 4, characterized in that the first lens (6) and the second lens (7) are each a general cylindrical lens.

7. Optical device (1) according to any one of the previous claims, characterized in that the stepped optical surface (8) of the second lens (7) comprises a larger number of active sections (9) and reset sections (10) alternating with each other per axial or radial length unit than the stepped optical surface (8) of the first lens (6).

8. Optical device (1) according to any one of the previous claims, characterized in that the second lens (7) is placed at a distance of between 0.001 mm and 1000 mm from the first lens (6).

9. Optical device (1) according to any one of the previous claims, characterized in that the beam shaping unit (3) is configured for converting a Gaussian beam into a flattened Gaussian beam.

10. Optical device (1) according to any one of the previous claims, characterized in that the beam shaping unit (3) comprises at least a negative lens (13) and a positive lens (14), wherein optionally the negative lens (13) and/or the positive lens (14) are achromatic and/or aspheric.

11. Optical device (1) according to claim 10, characterized in that the beam shaping unit (3) comprises a condenser, wherein the positive lens (14) is arranged in the optical path of the light beam (2) between the negative lens (13) and the condenser lens.

12. Optical device (1) according to any one of the previous claims, wherein the focusing unit (5) comprises at least a positive lens (15).

13. Optical device (1) according to any one of the previous claims, characterized by an aperture (16, 17), in particular a soft aperture.

14. Optical device (1) according to any one of the previous claims, characterized in that the lens system (4) is arranged in the optical path of the light beam (2) between the beam shaping unit (3) and the focusing unit (5).

15. Optical device (1) according to any one of the previous claims, characterized by a light source, which is optionally coherent or semi-coherent, in particular a laser, wherein optionally the beam shaping unit (3) is arranged in the optical path of the light beam (2) closer to the light source than the lens system (4) and the focusing unit (5).

Abstract:

Optical device (1) for controlling a light beam (2) comprising:

- a beam shaping unit (3) for increasing the uniformity of the spatial intensity profile of the light beam (2);
- a lens system (4); and
- a focusing unit (5);

wherein

the lens system comprises a first lens (6) and a second lens (7), wherein each of the first lens (6) and the second lens (7) comprises a stepped optical surface (8) formed by active sections (9) and reset sections (10) alternating with each other, wherein the active sections (9) stepwise form a surface profile (11), which is aspheric, wherein the stepped optical surface (8) of the first lens (6) faces the stepped optical surface (8) of the second lens (7).

(Fig. 1)

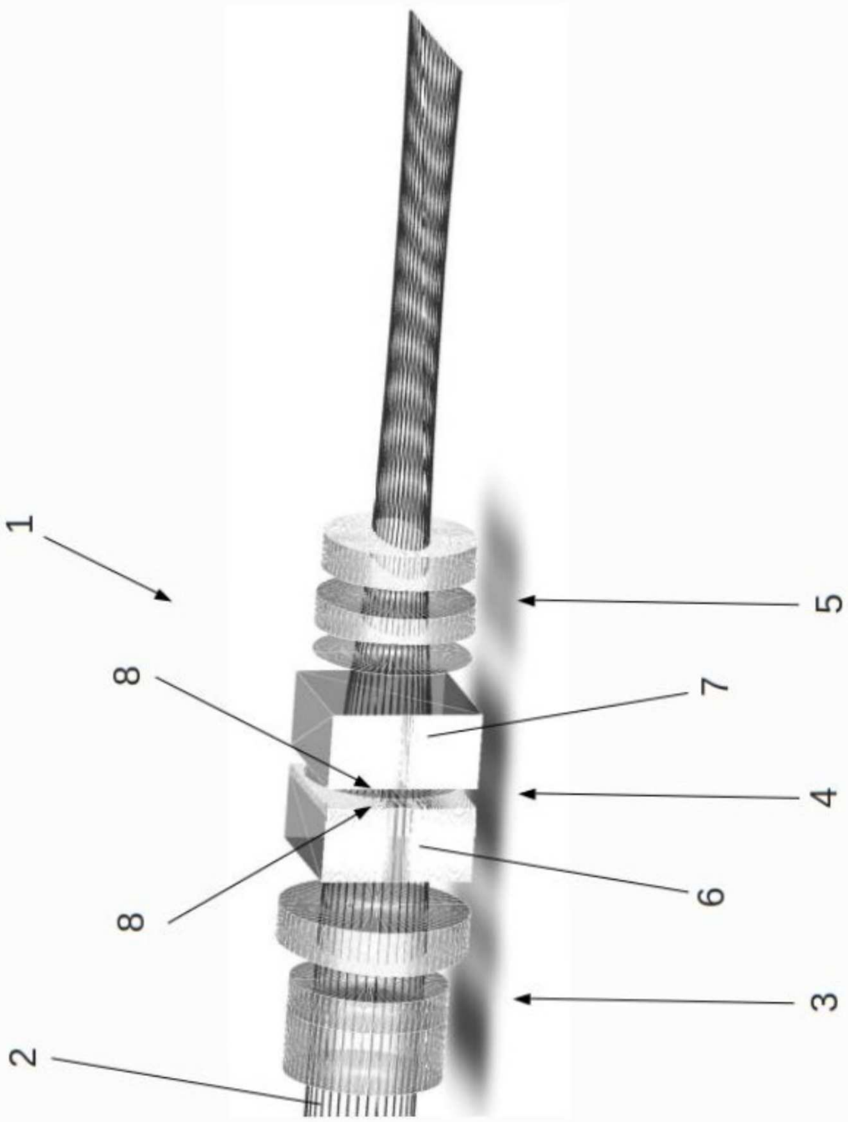


Fig. 1

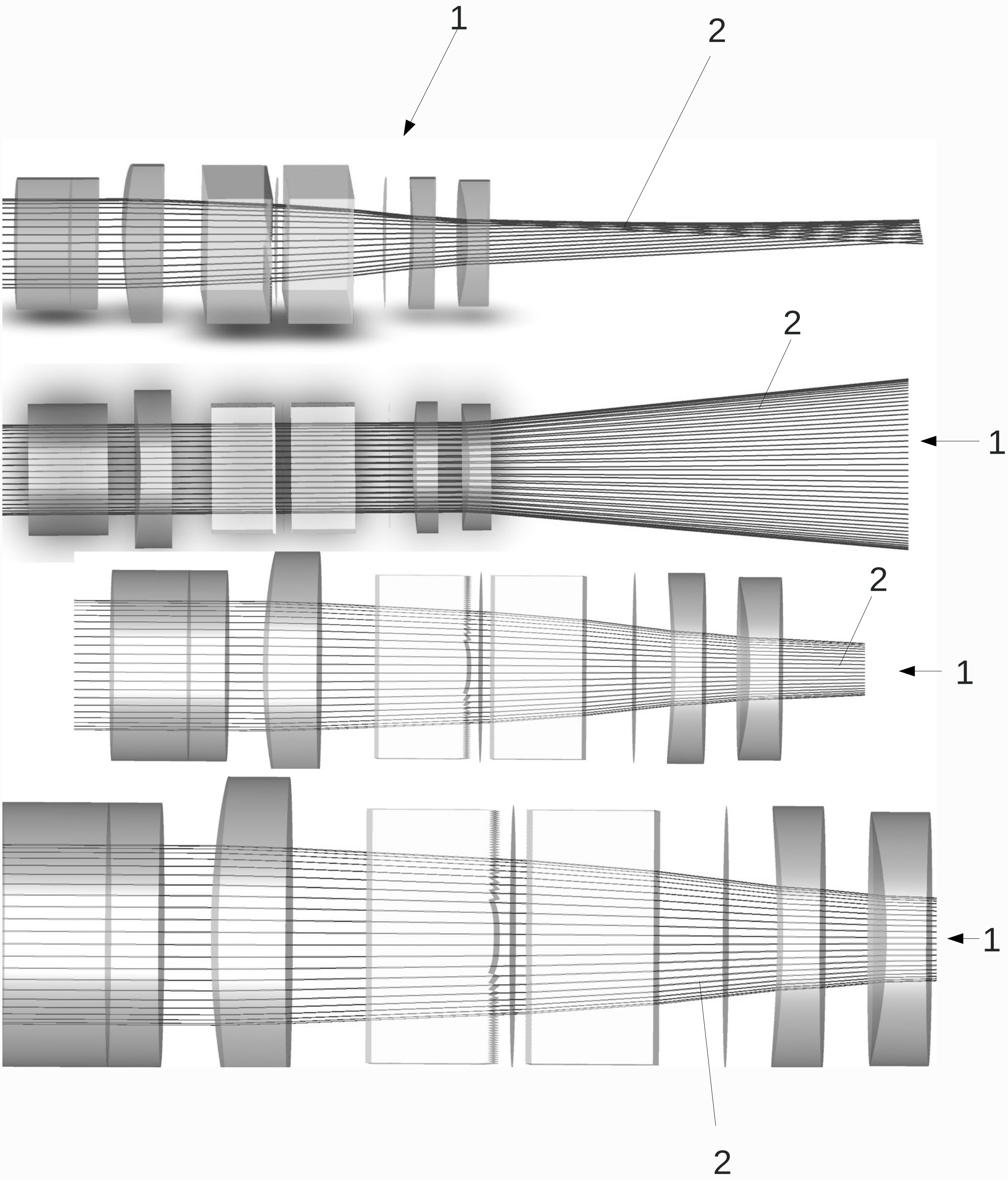


Fig. 2

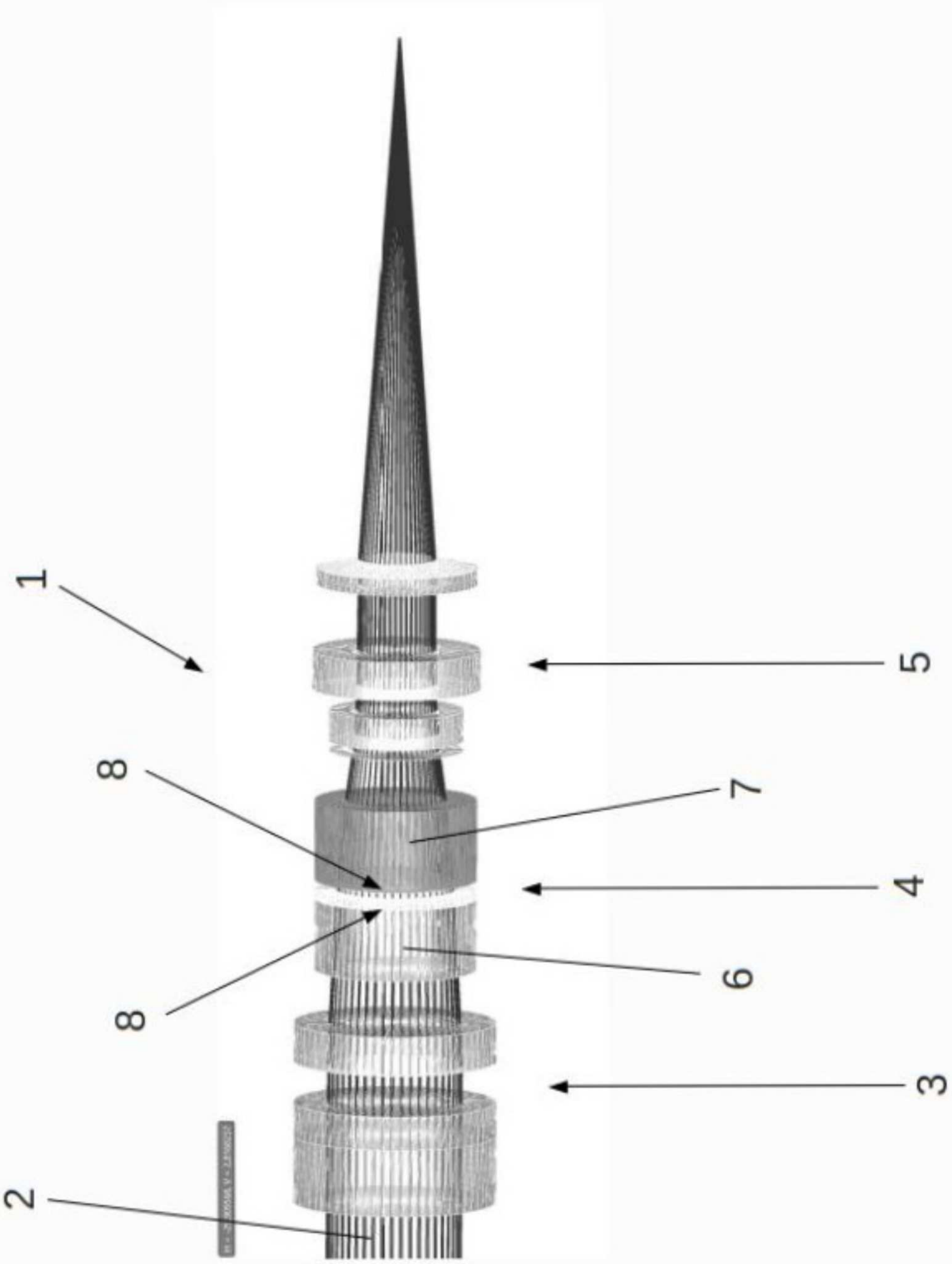


Fig. 3

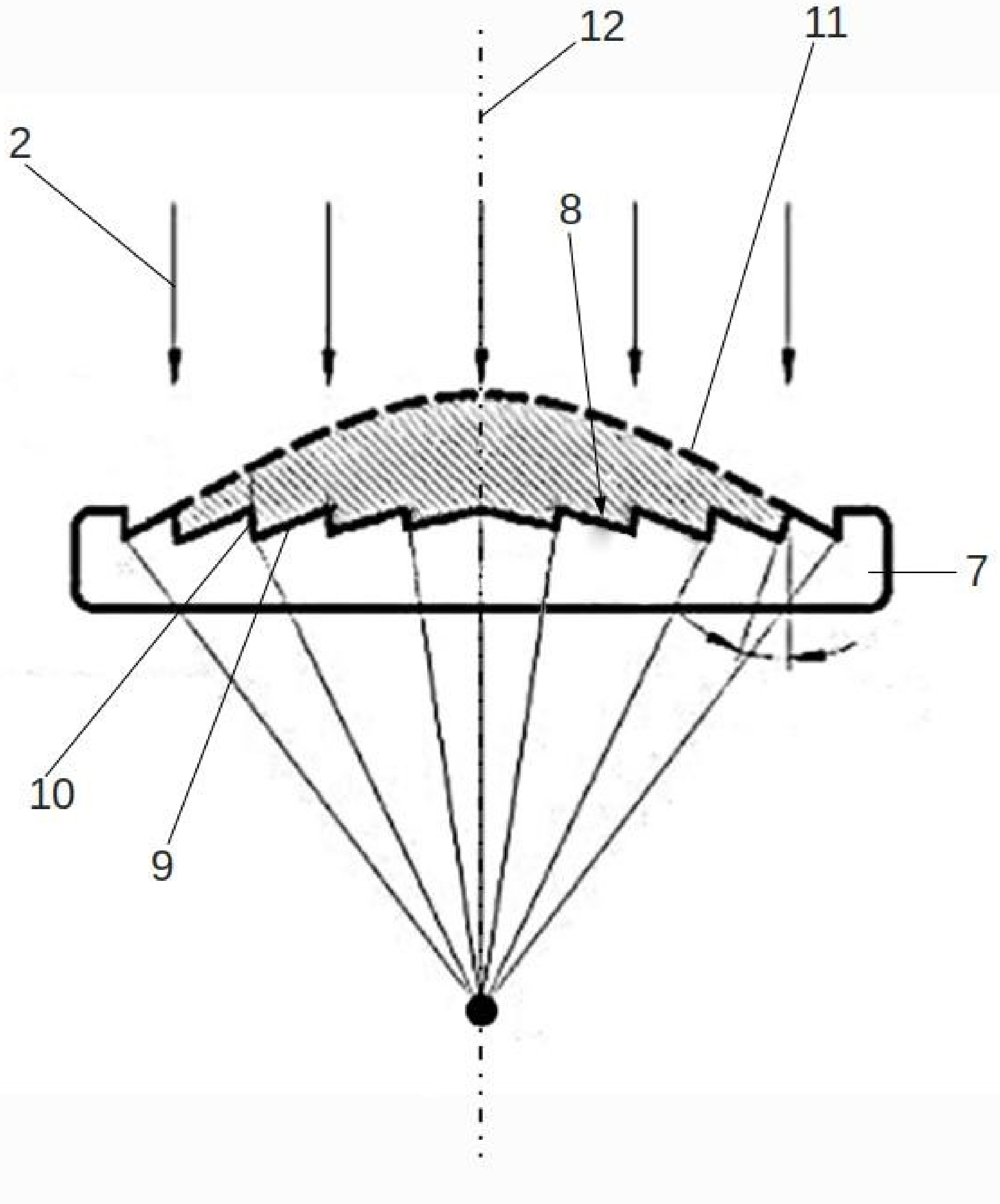


Fig. 4

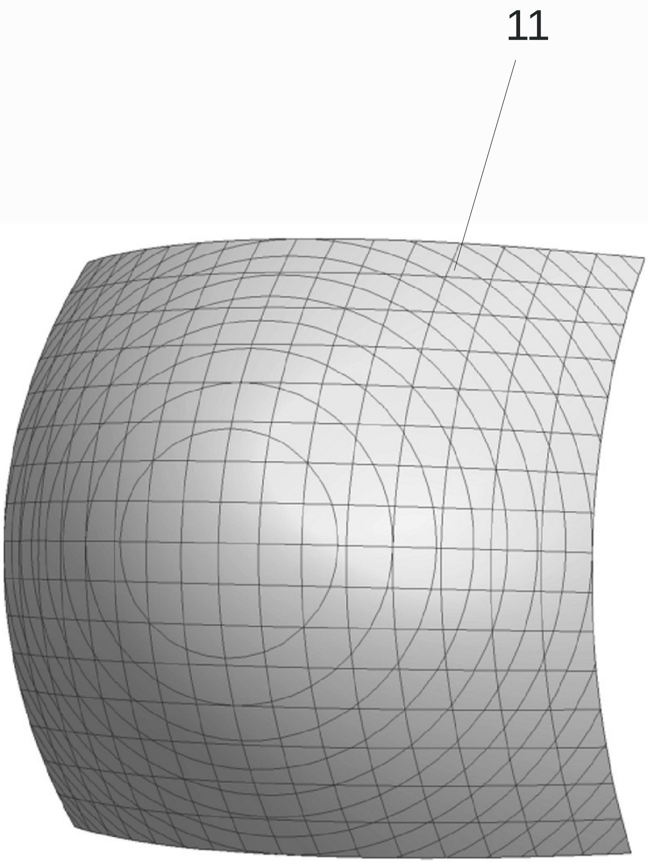


Fig. 5a

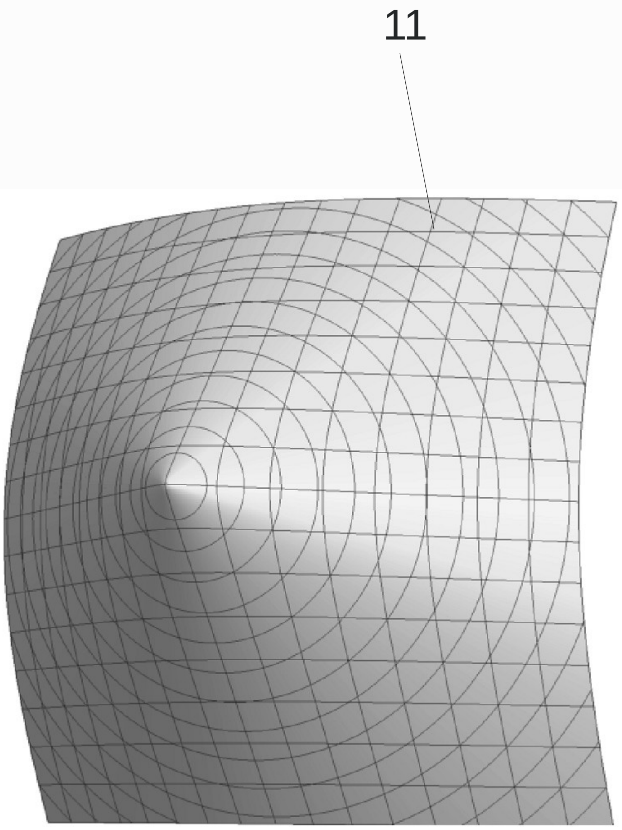


Fig. 5b

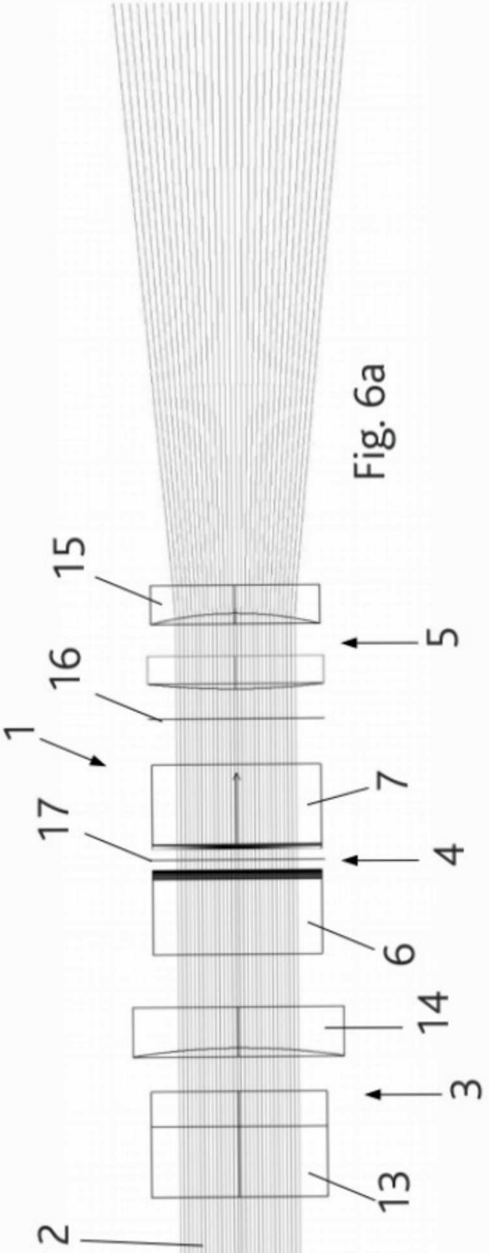


Fig. 6a

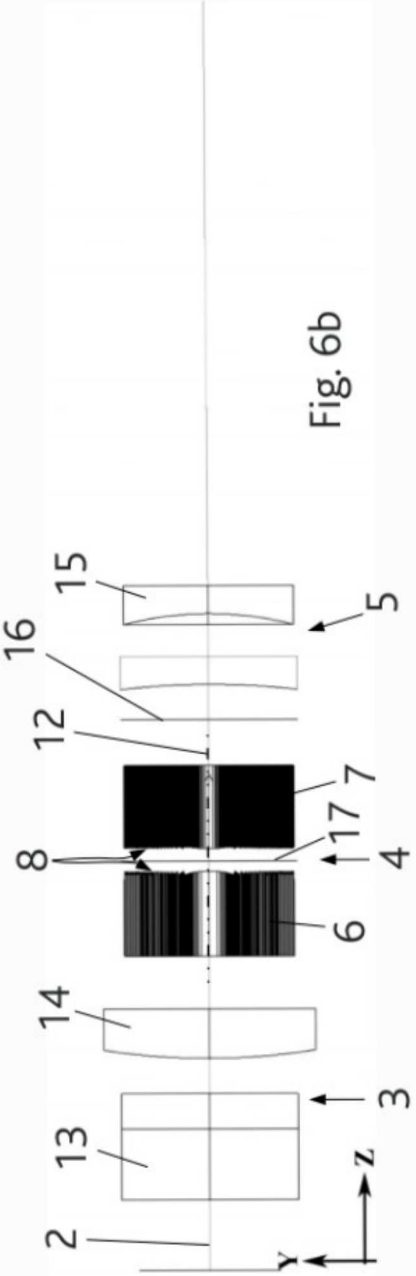


Fig. 6b

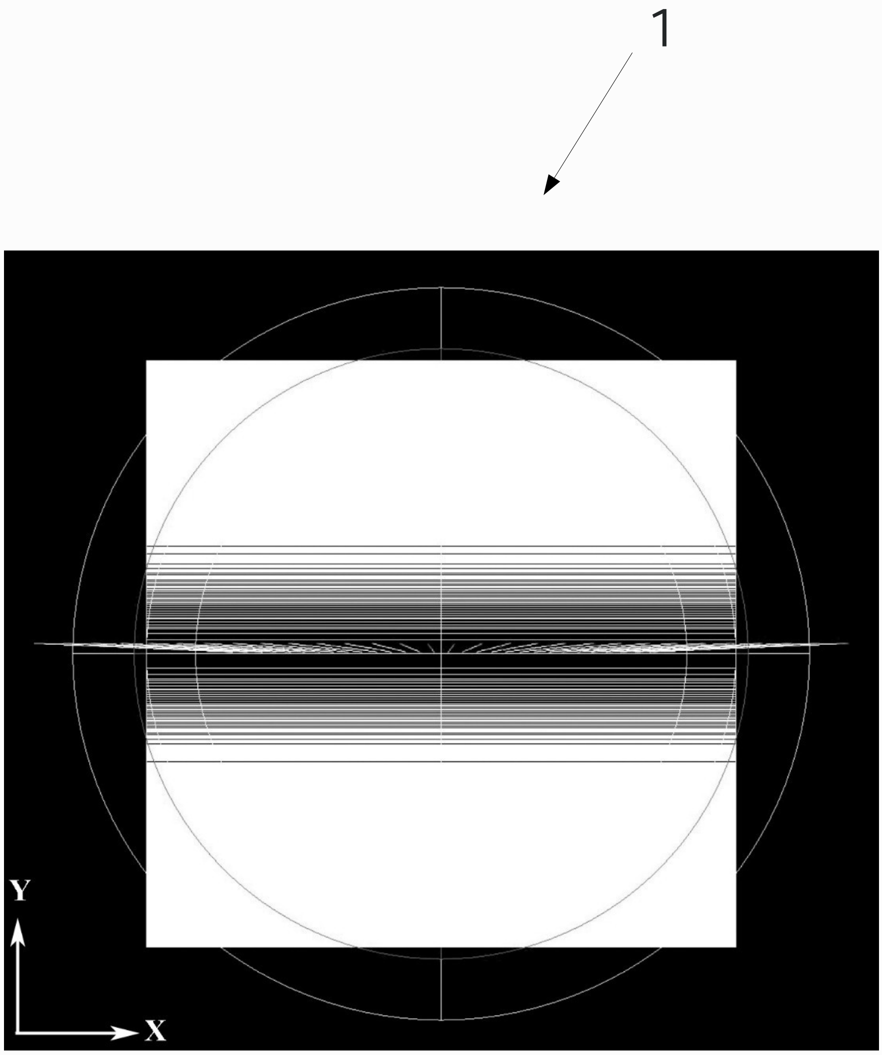


Fig. 6c

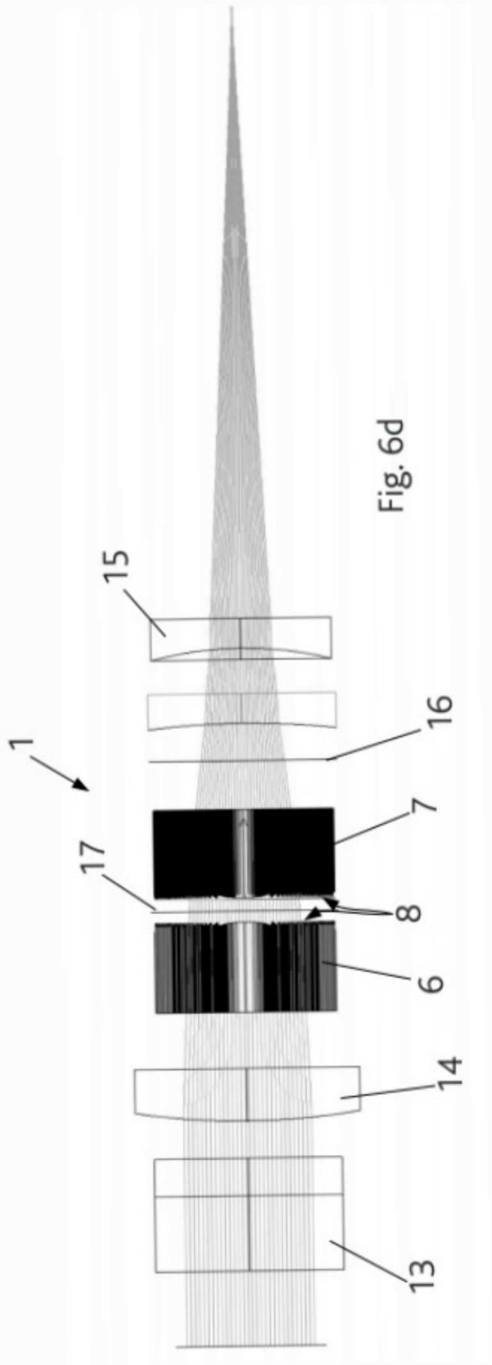


Fig. 6d

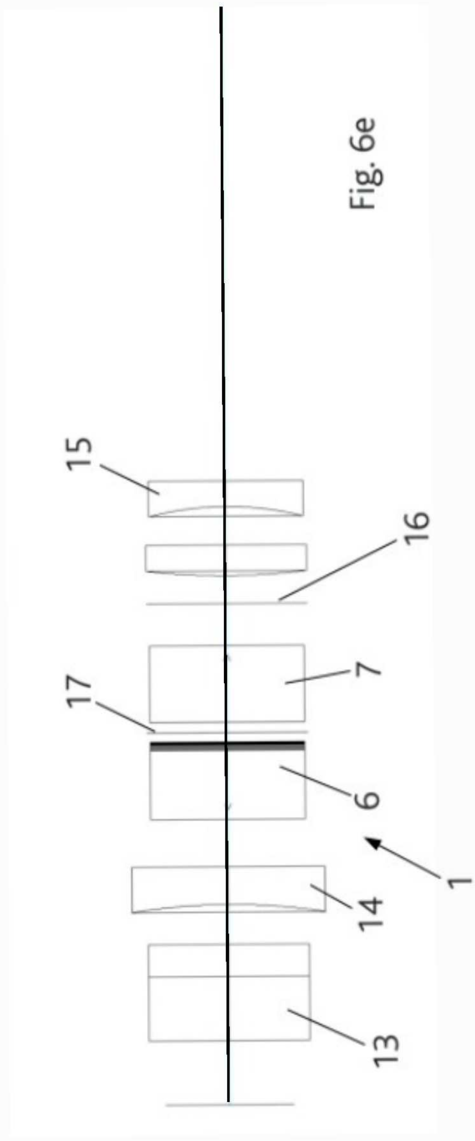


Fig. 6e

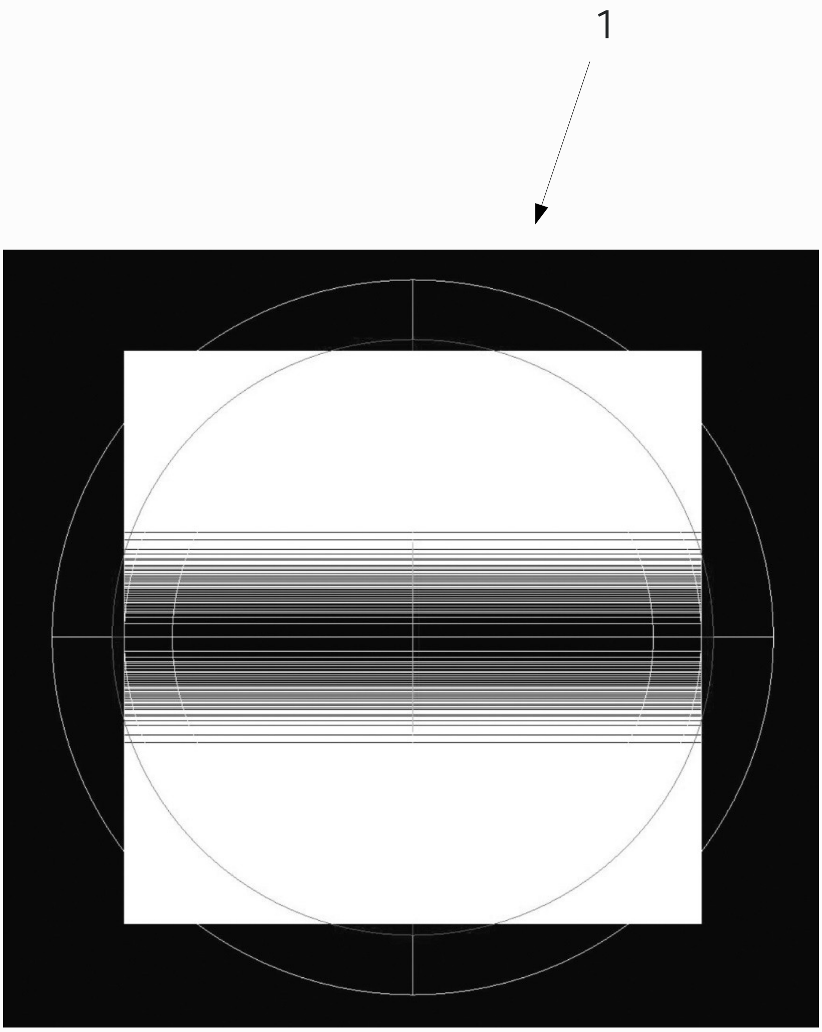


Fig. 6f

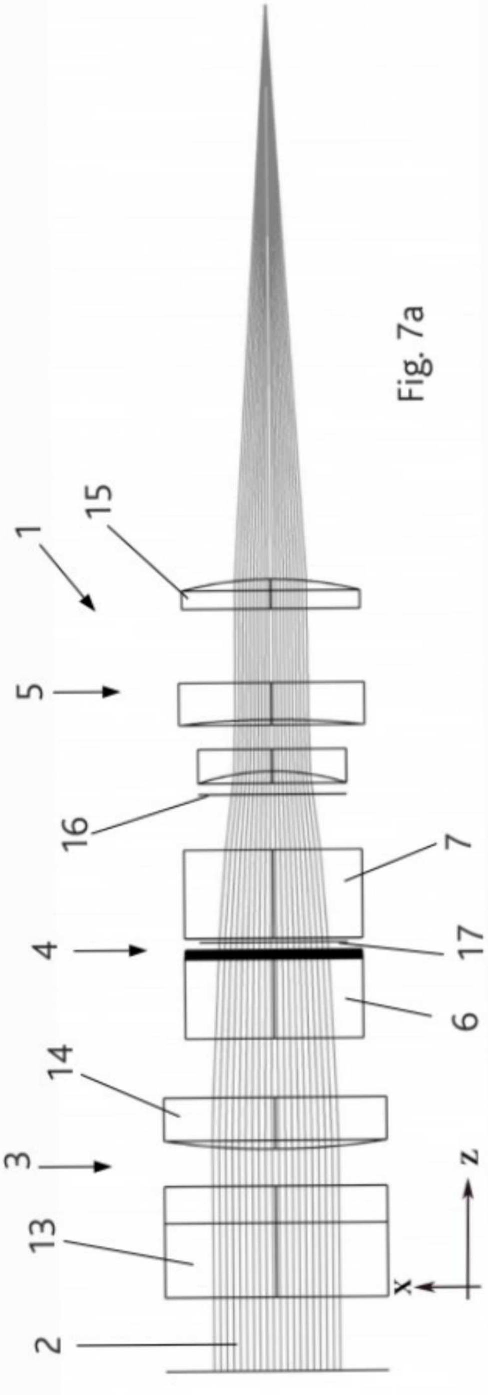


Fig. 7a

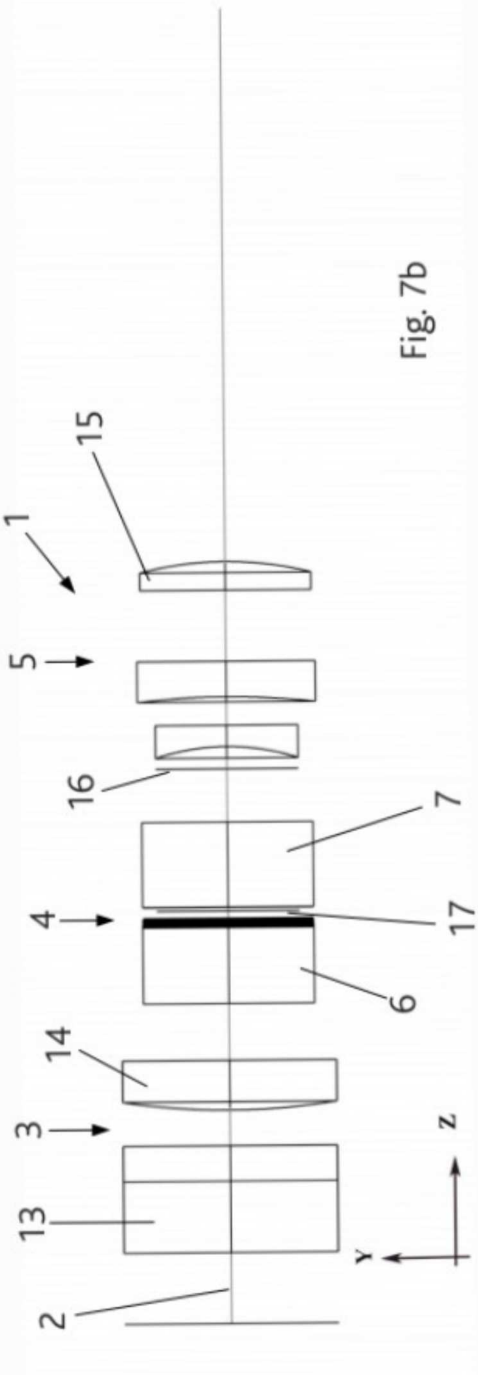


Fig. 7b

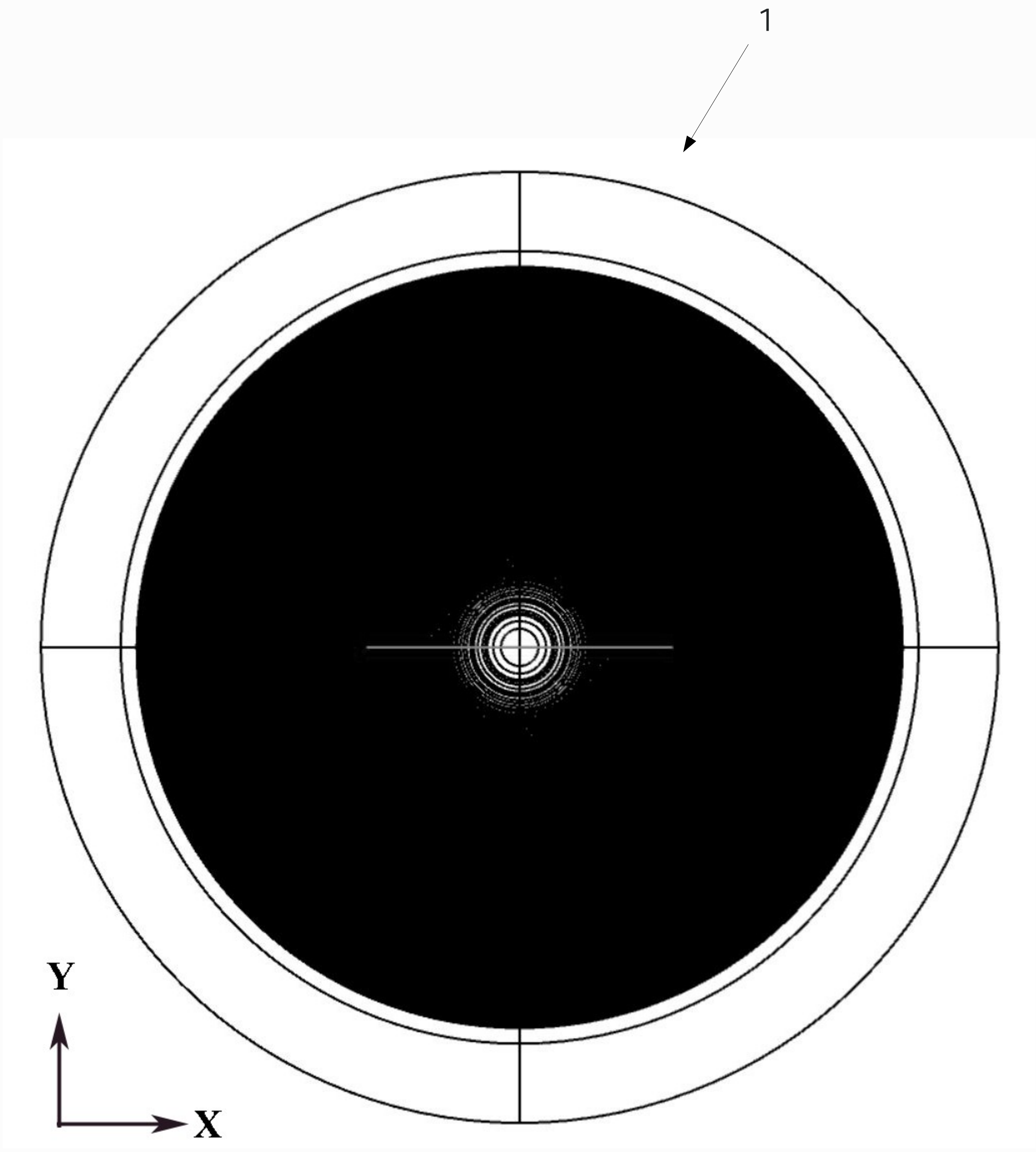


Fig. 7c

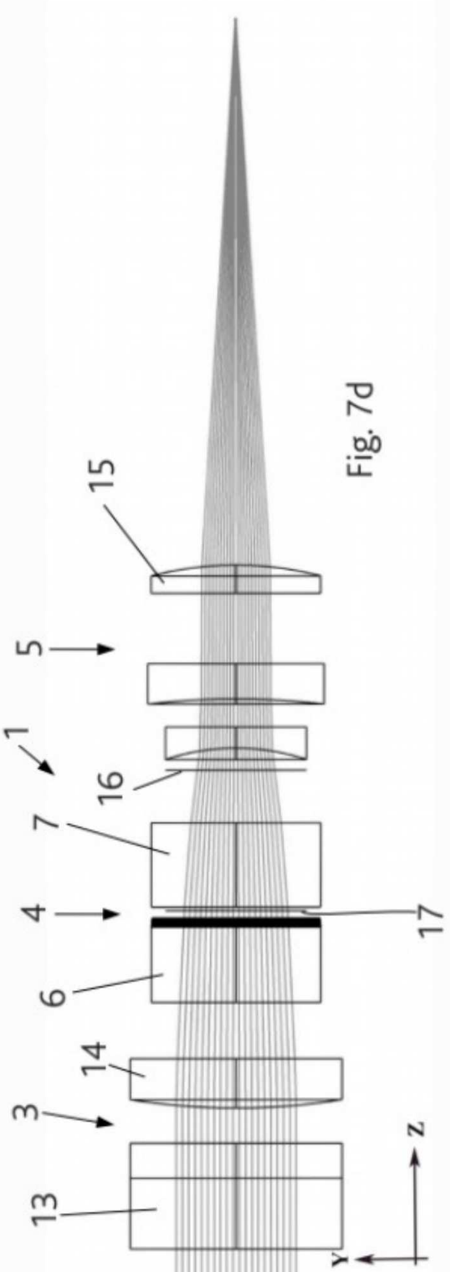


Fig. 7d

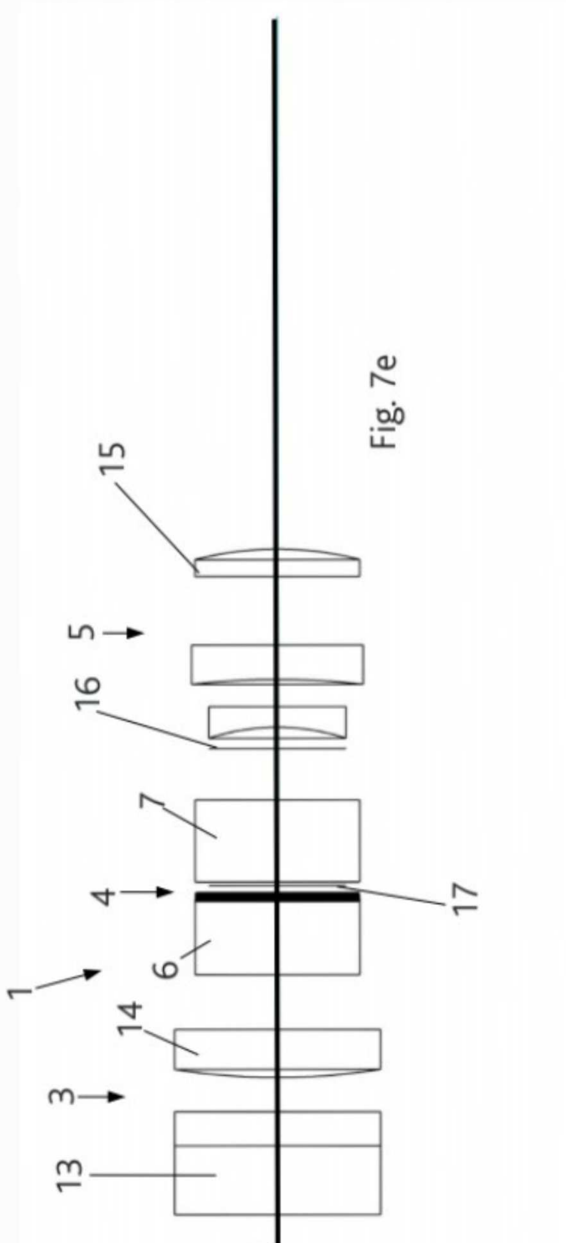


Fig. 7e

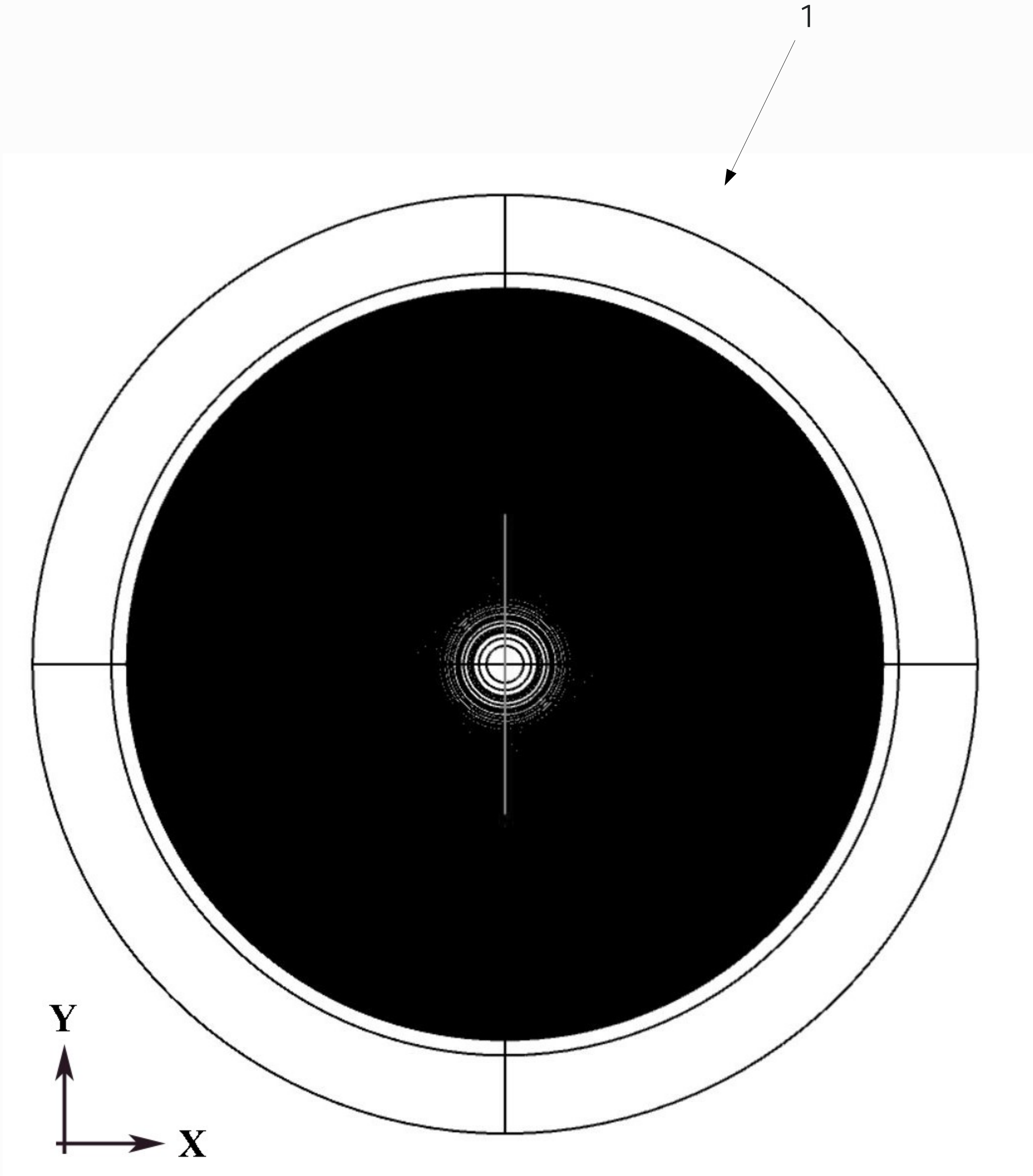


Fig. 7f

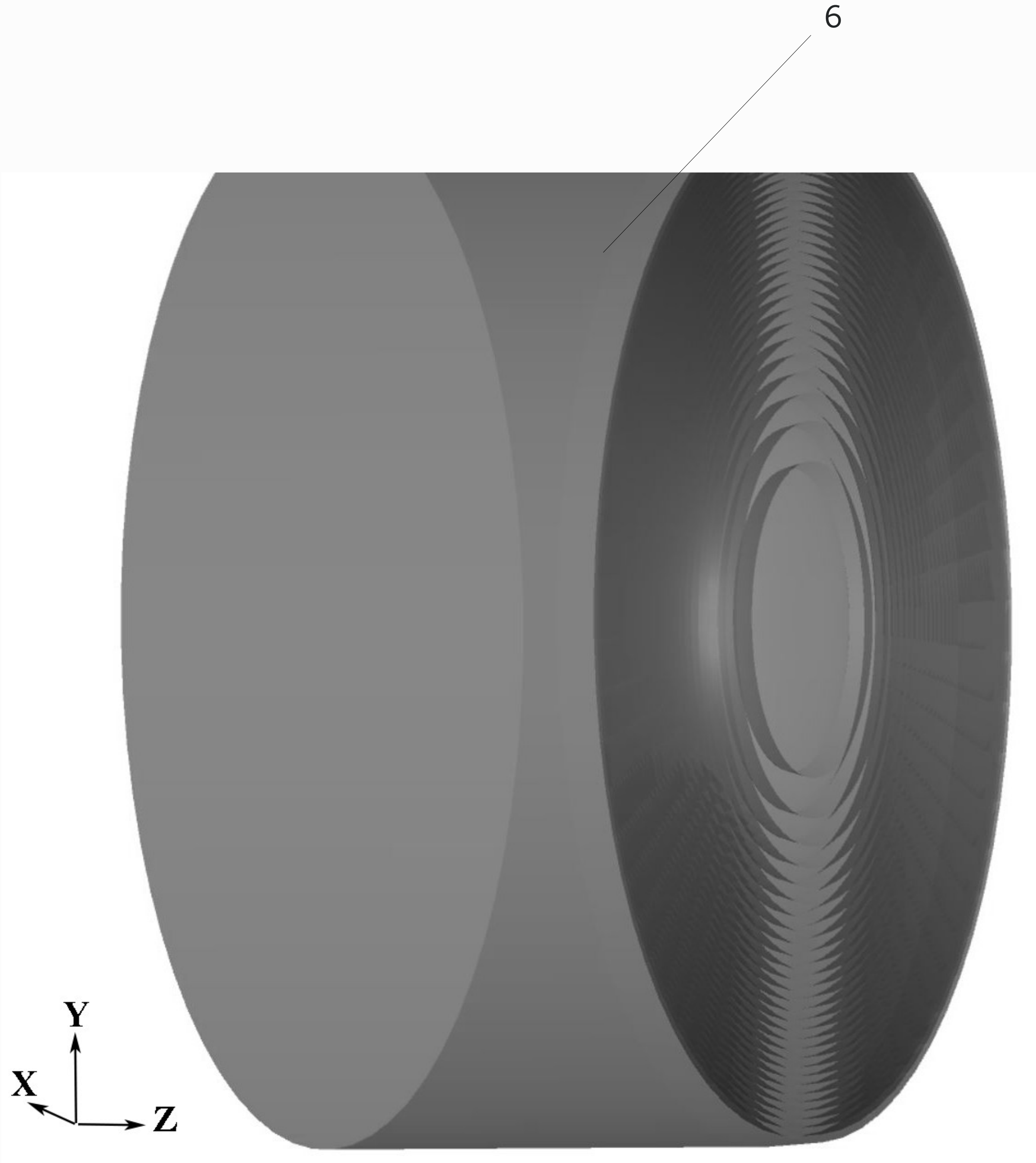


Fig. 8a

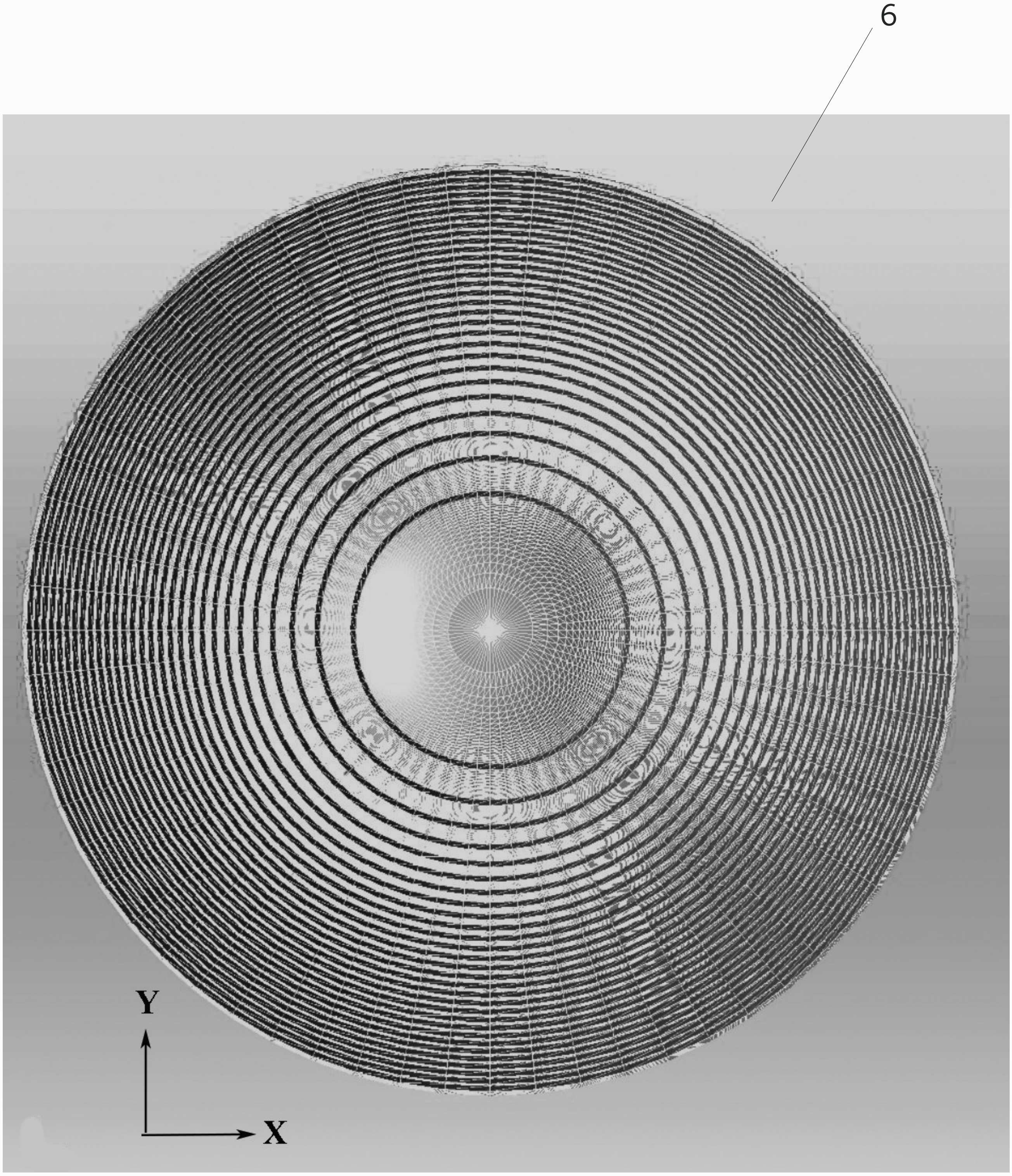


Fig. 8b

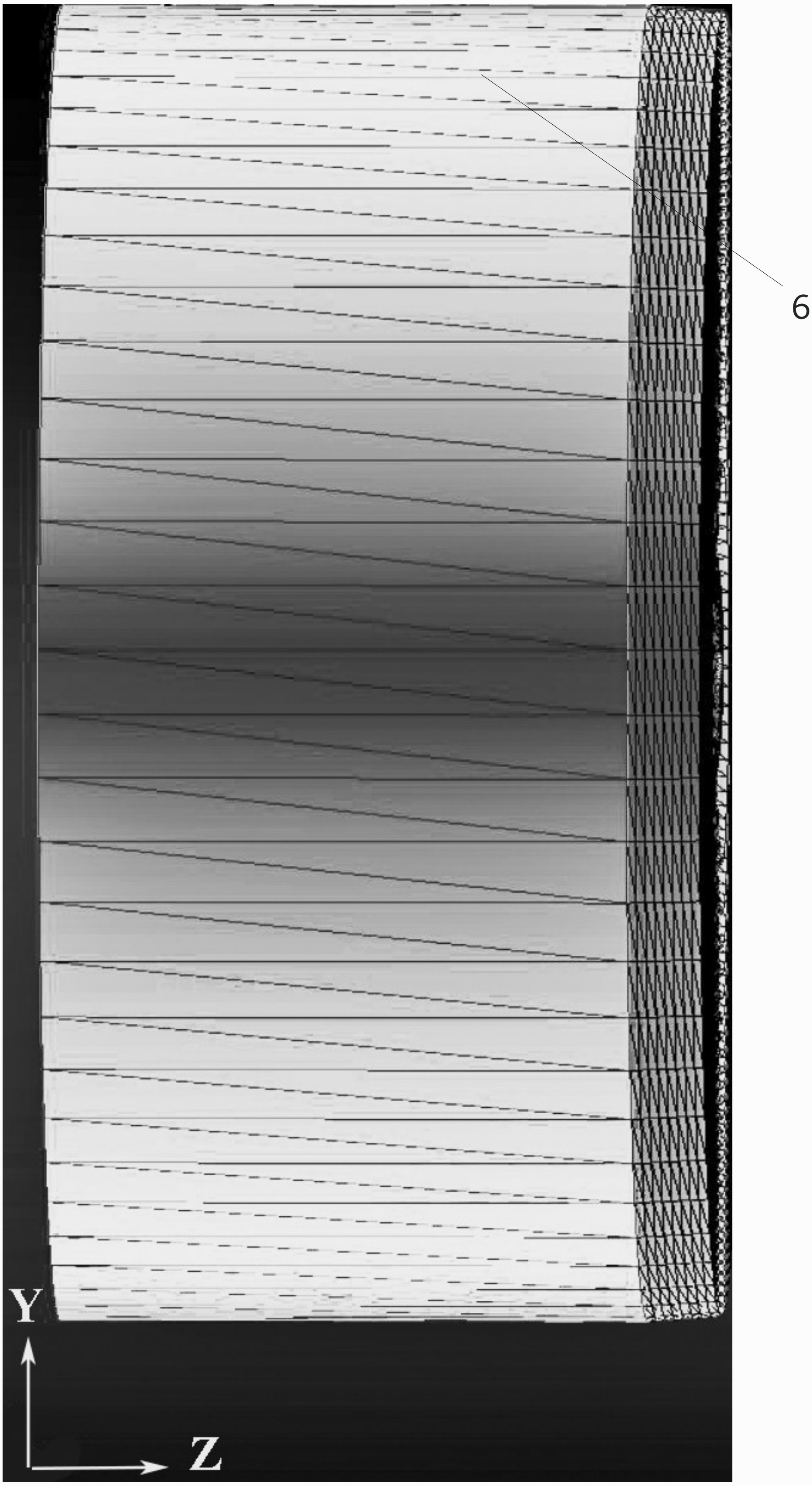


Fig. 8c

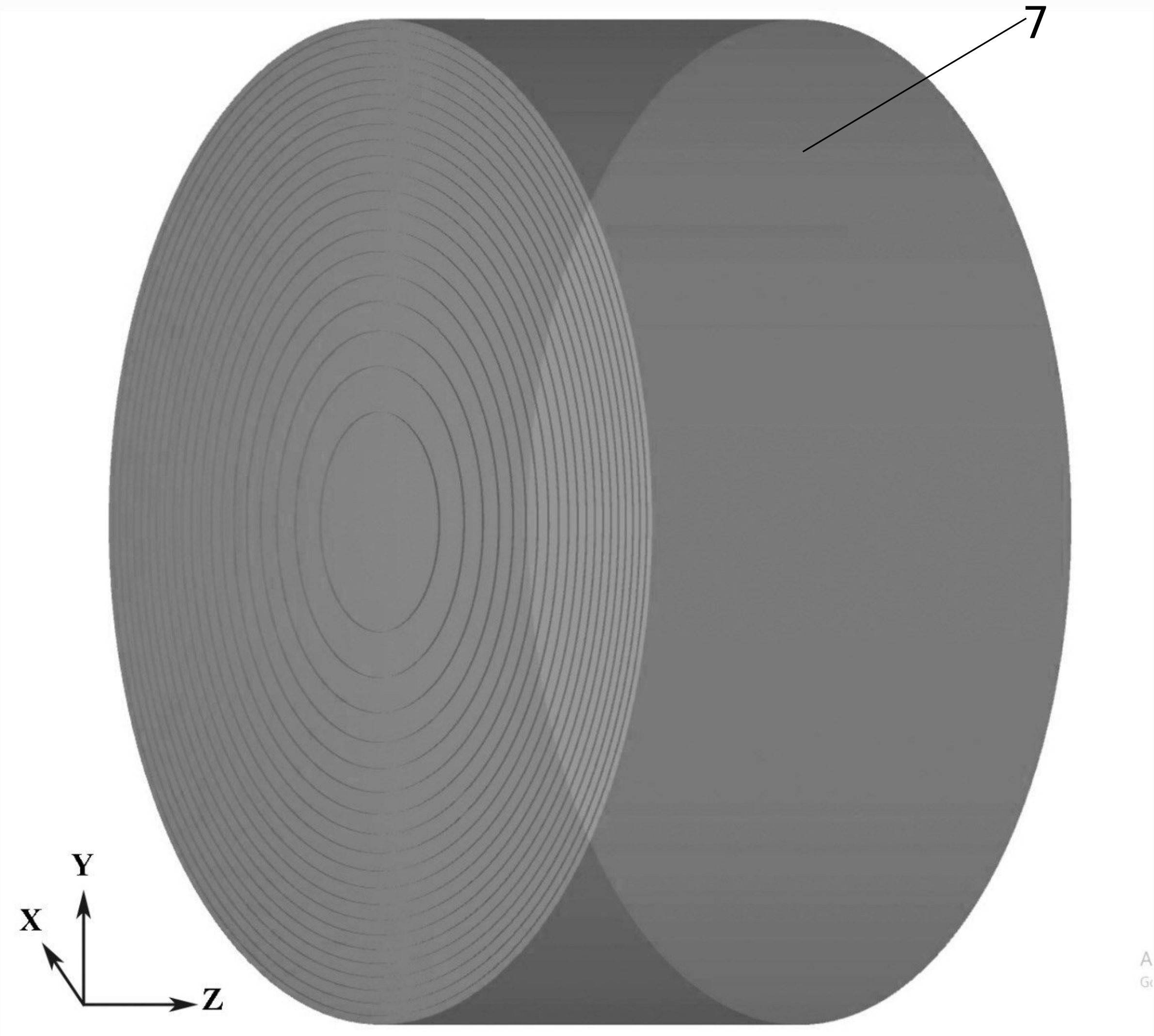


Fig. 9a

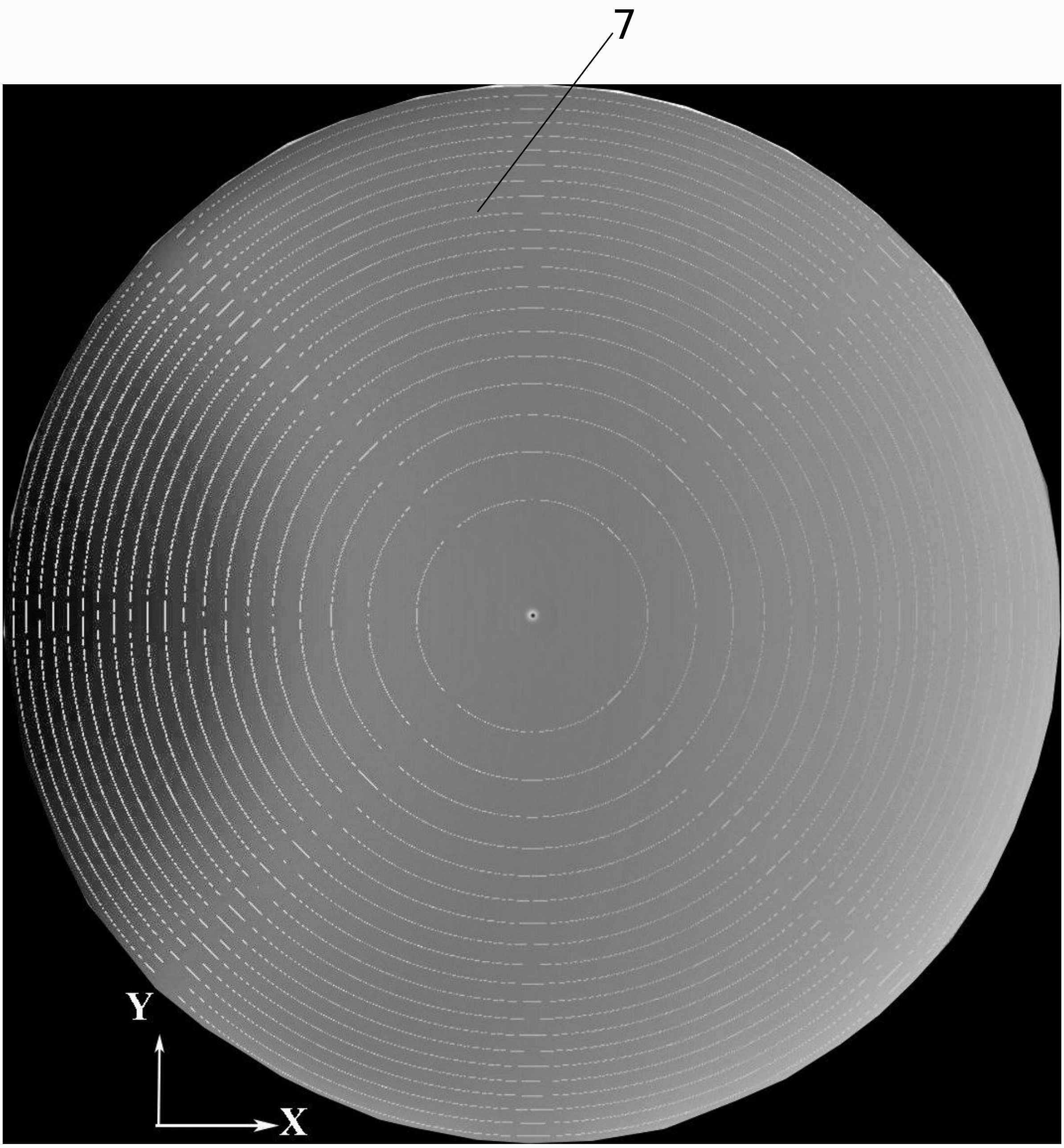


Fig. 9b

Fig. 9c

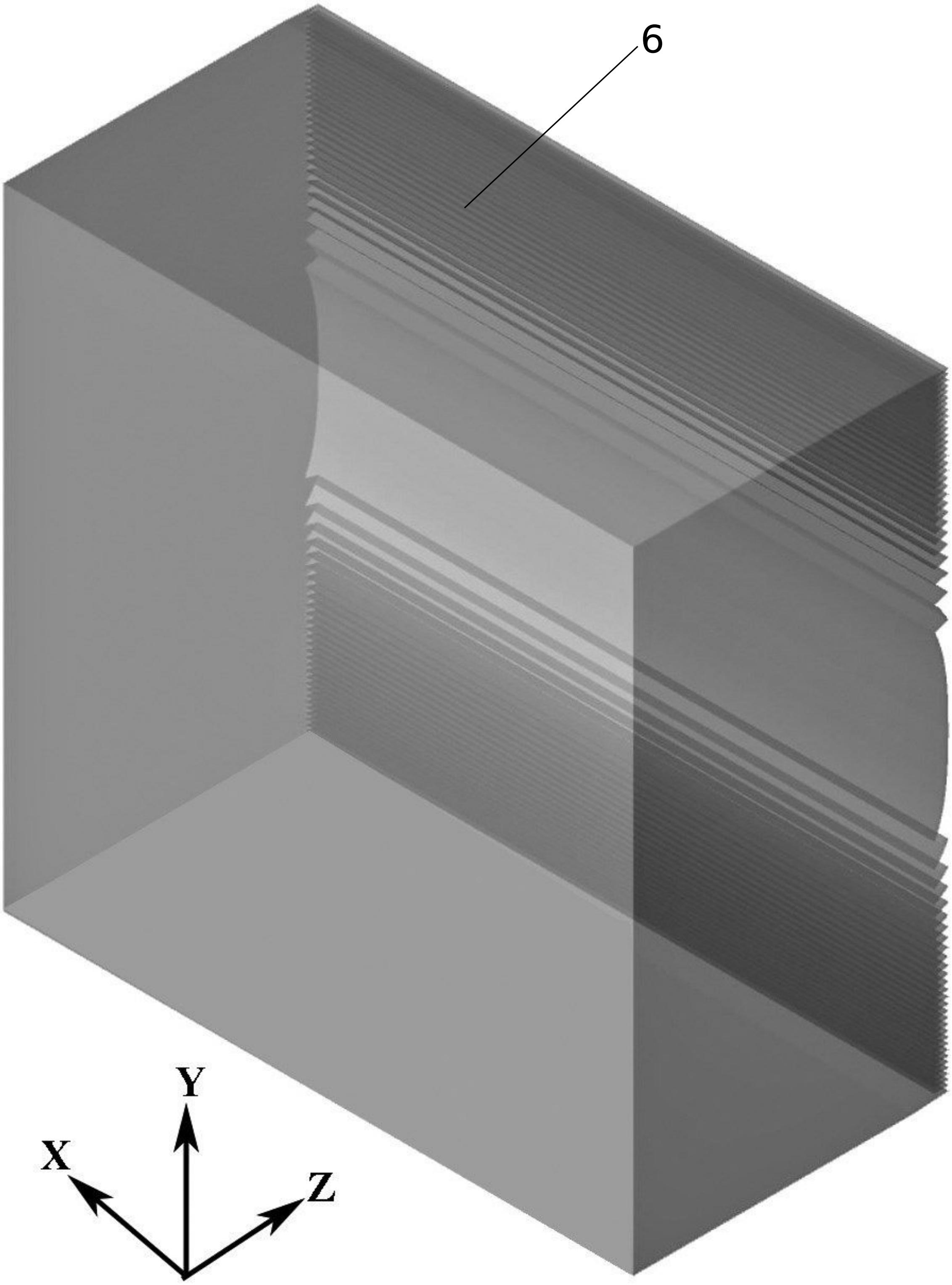


Fig. 10a

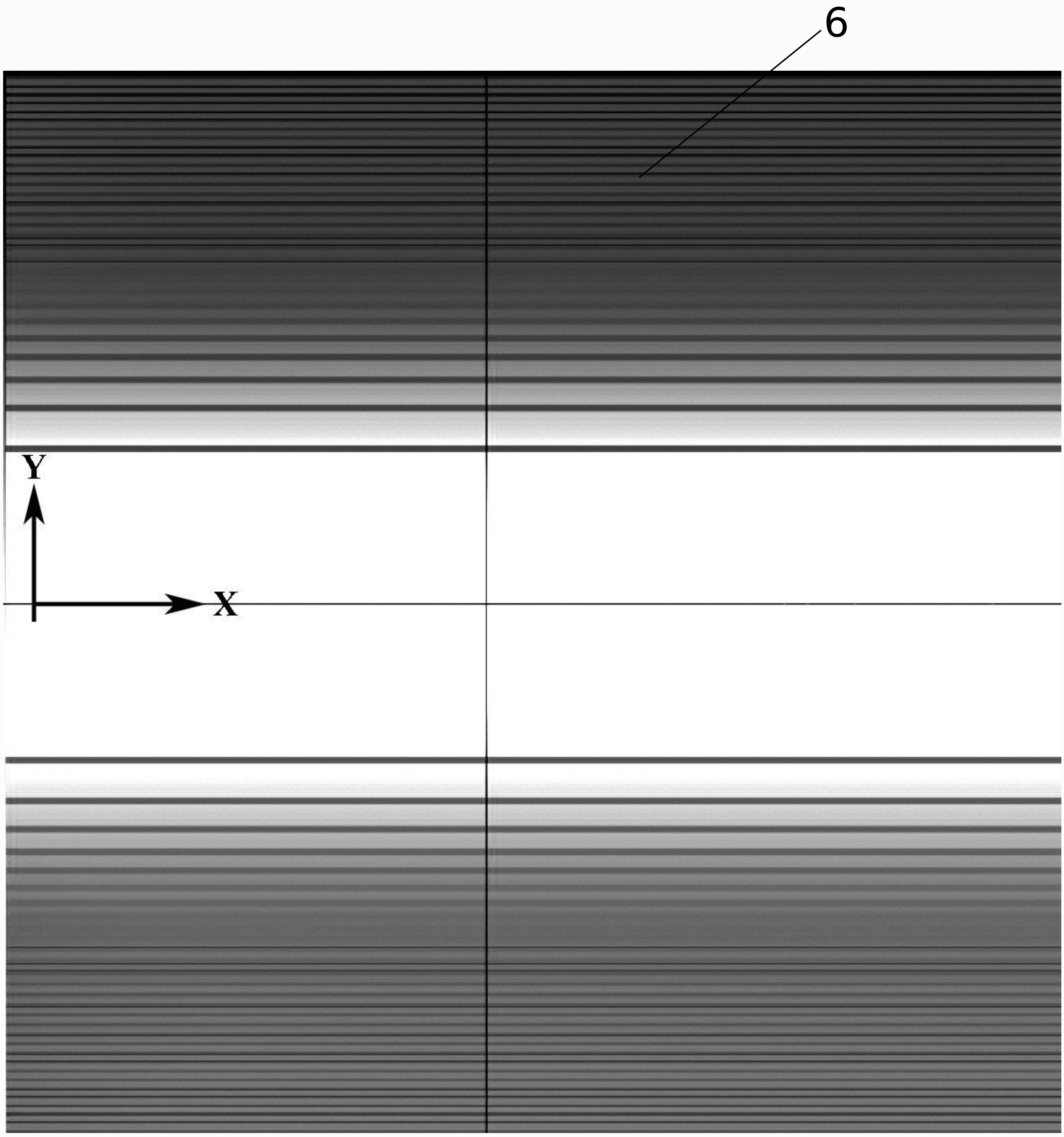


Fig. 10b

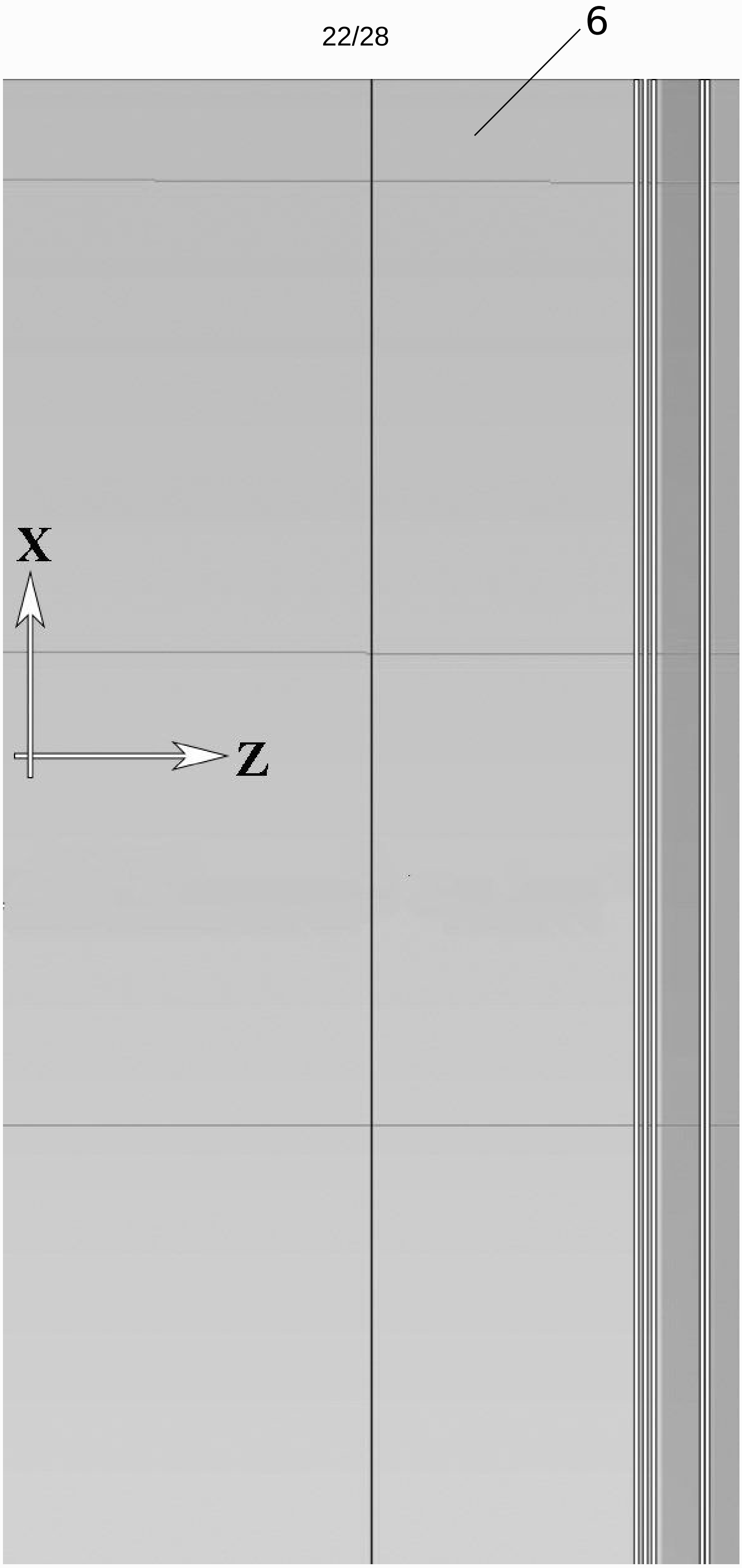


Fig. 10c

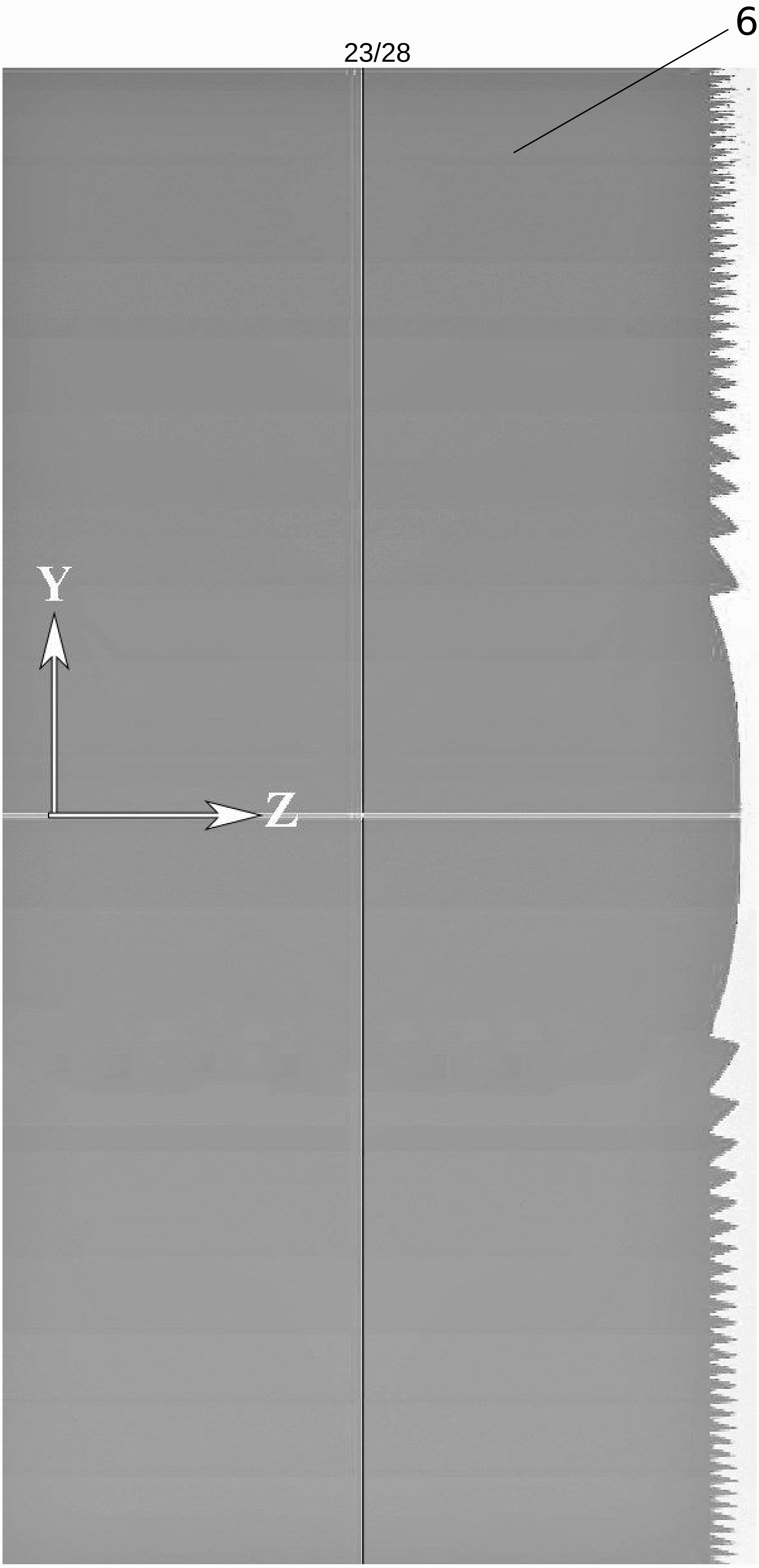


Fig. 10d

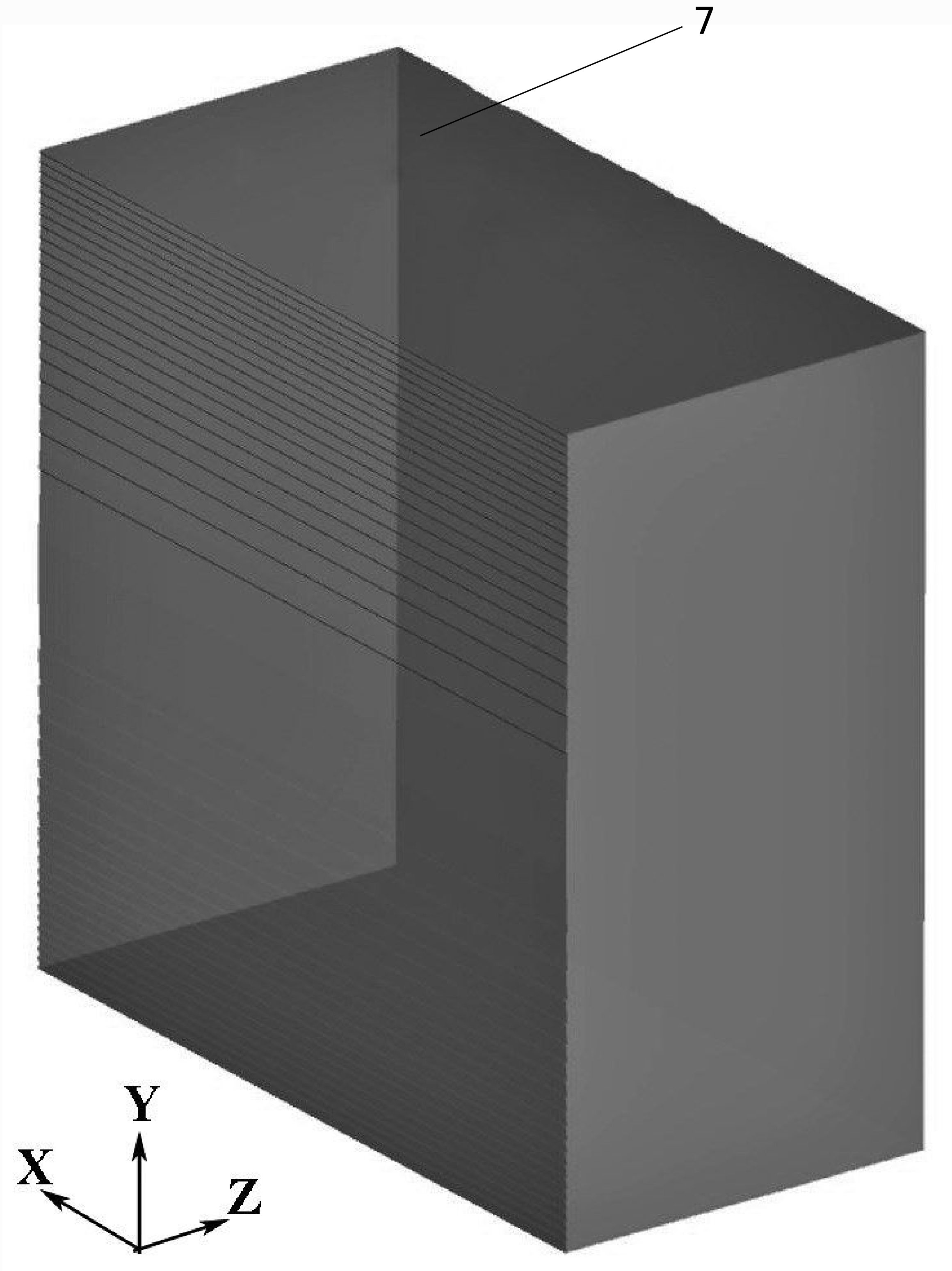


Fig. 11a

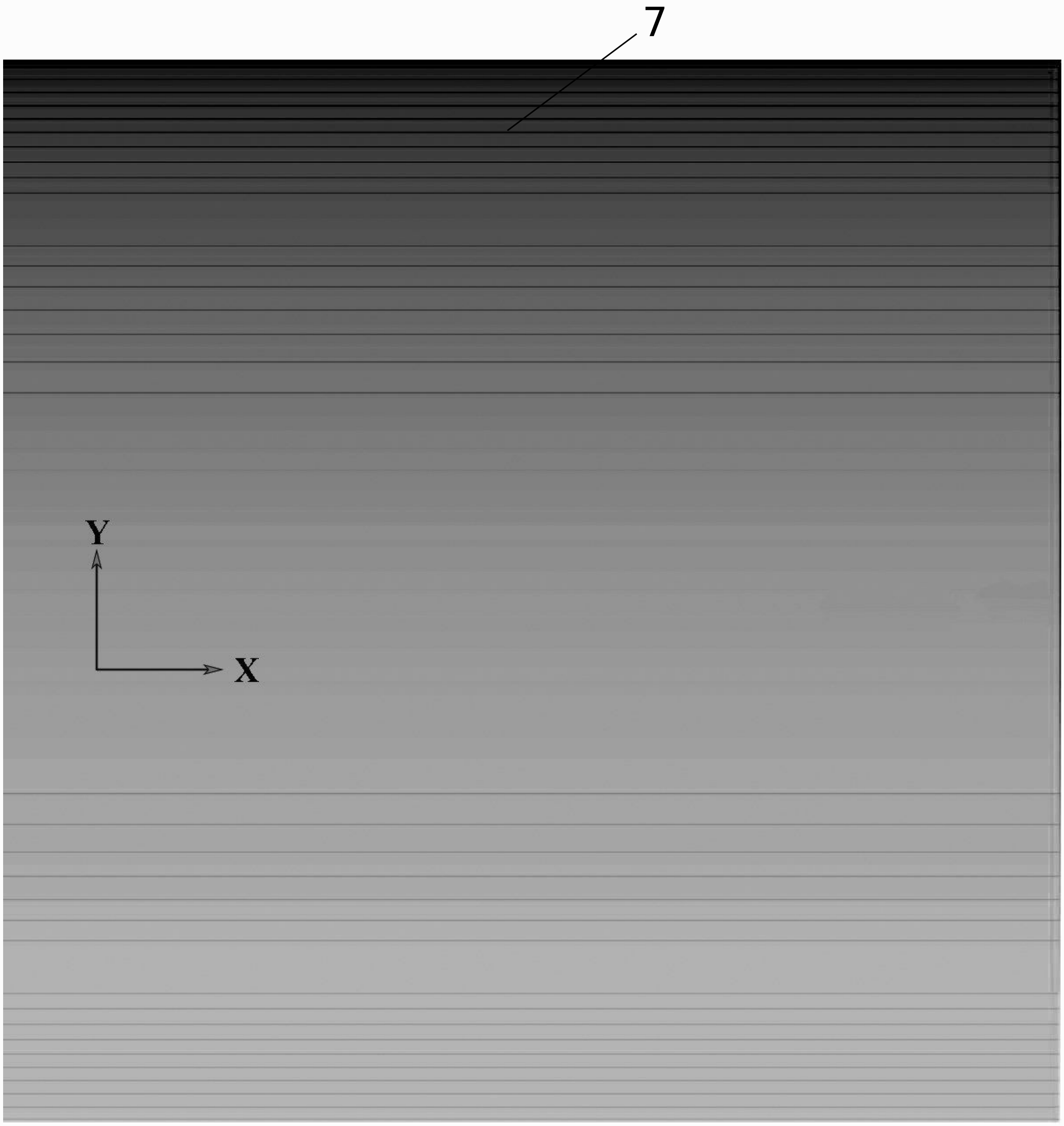


Fig. 11b

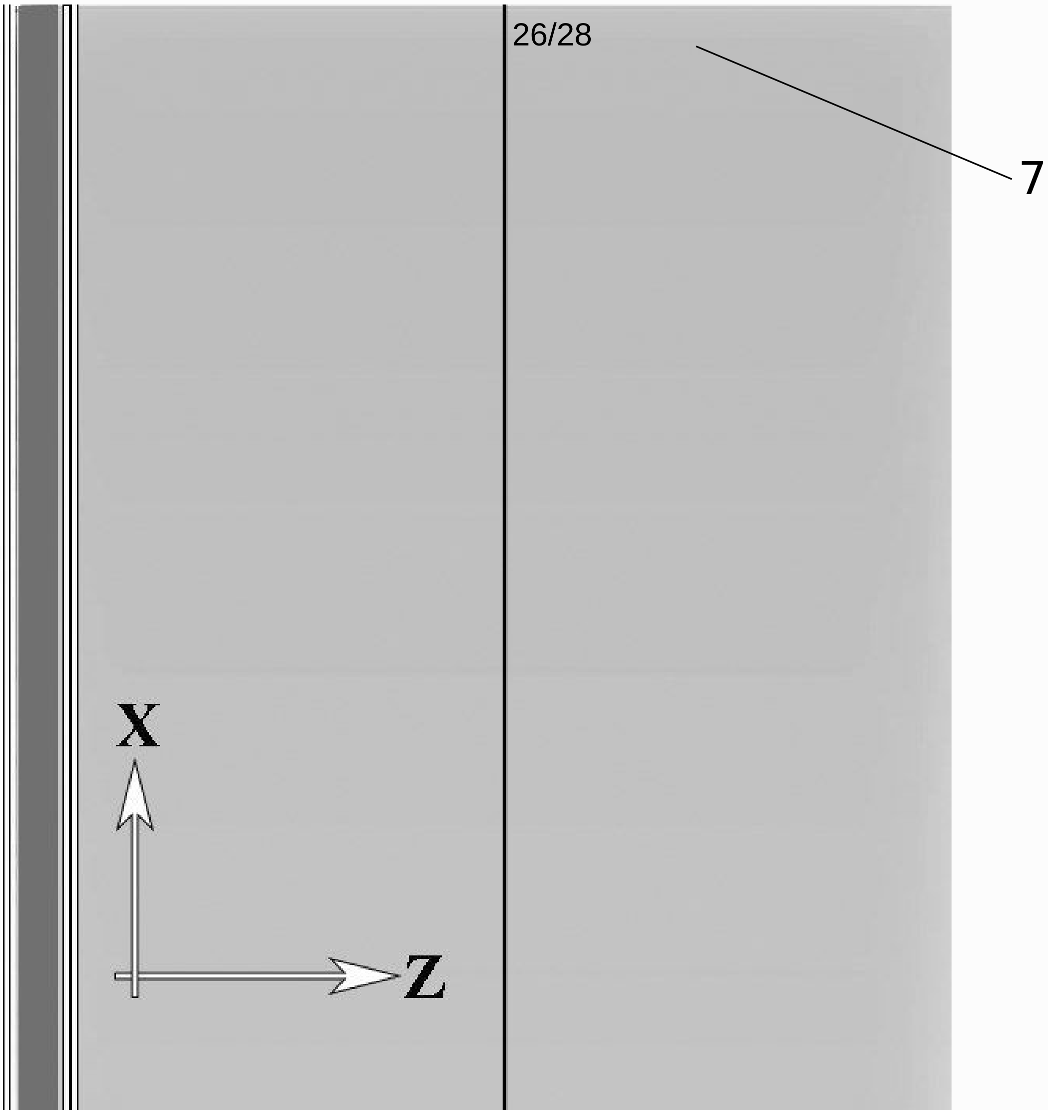


Fig. 11c

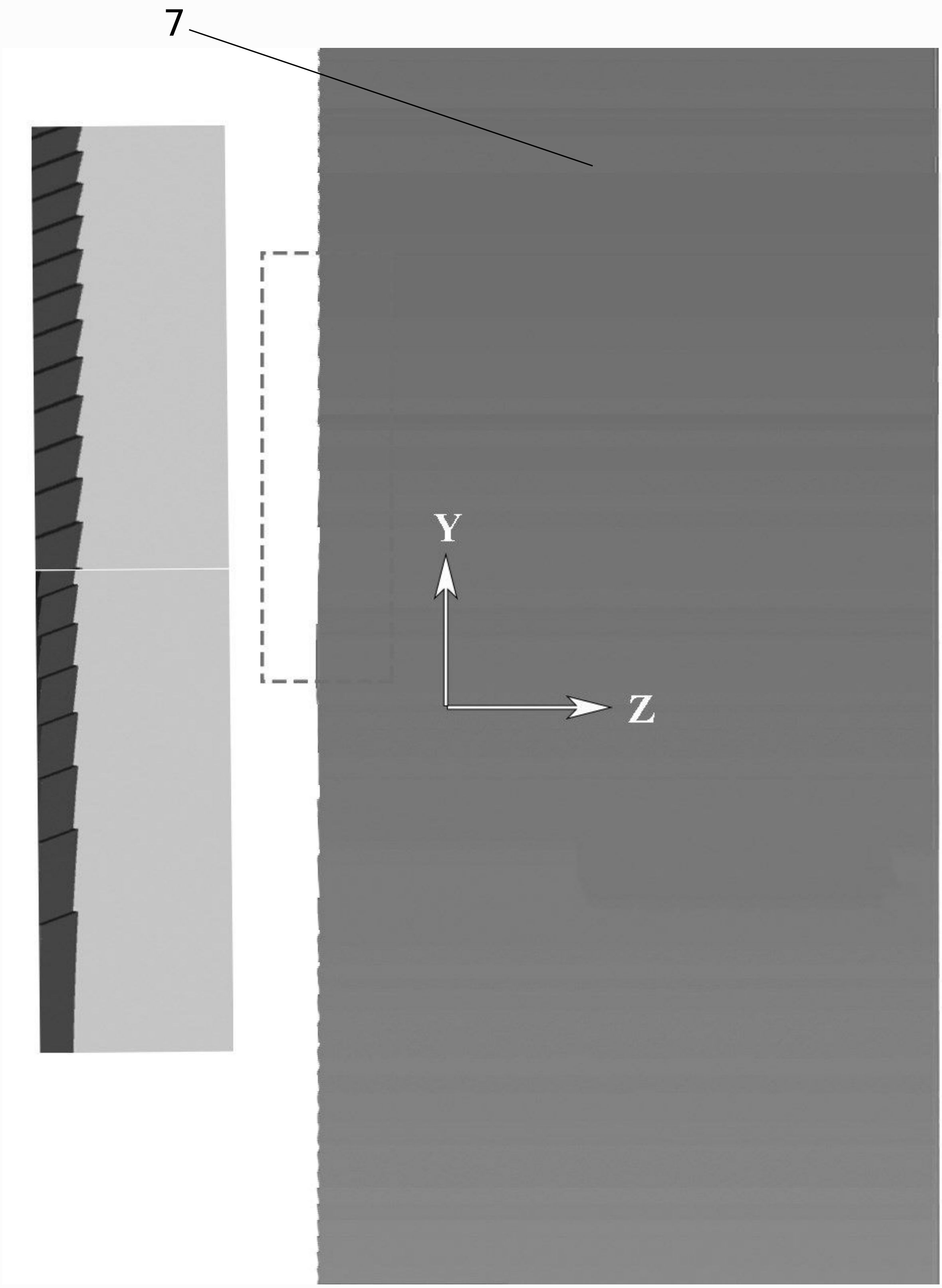
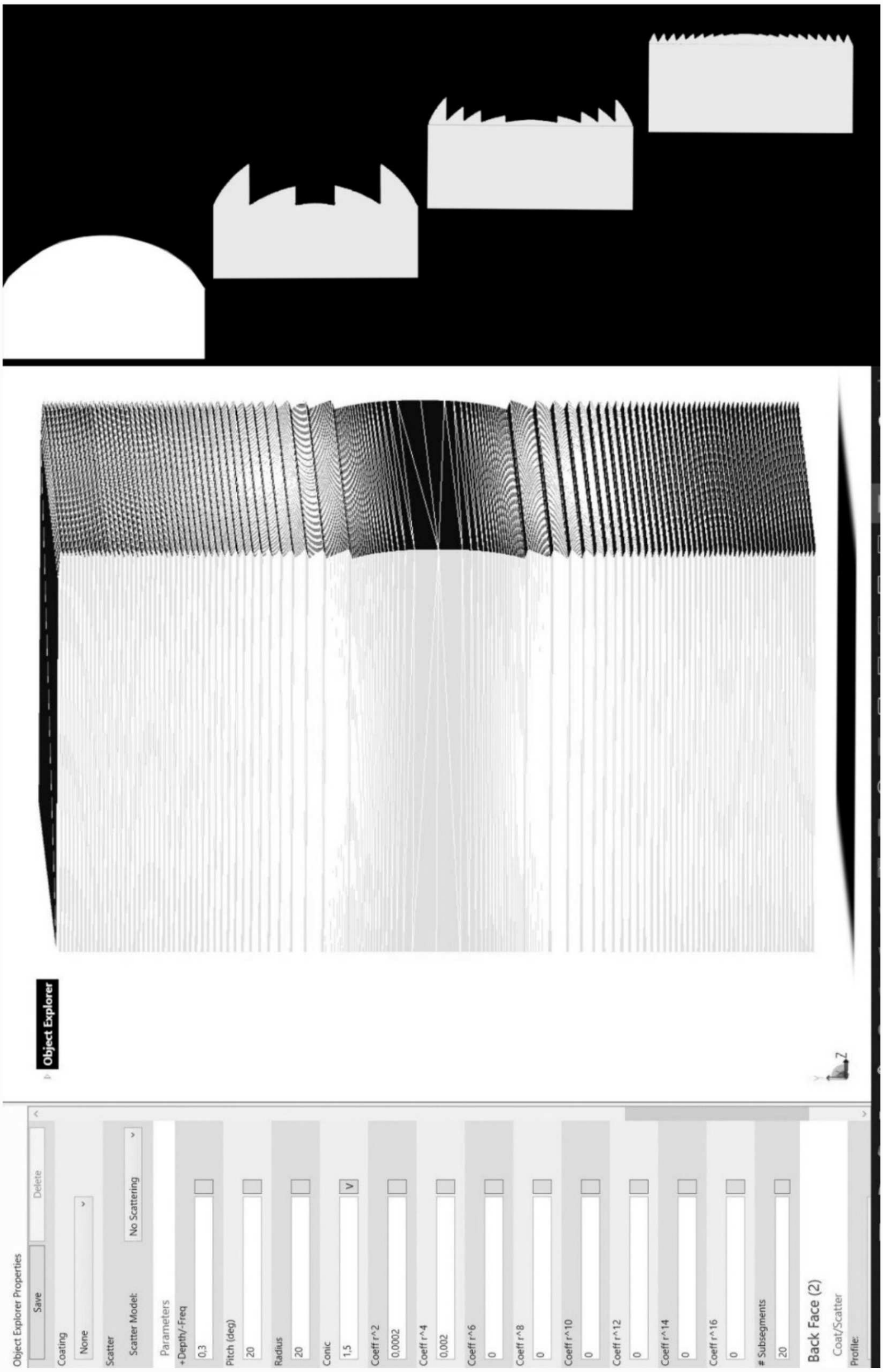


Fig. 11d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Radius
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Conic
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Coeff r^2
0,0002
Coeff r^4
0,002
Coeff r^6
0
Coeff r^8
0
Coeff r^10
0
Coeff r^12
0
Coeff r^14
0
Coeff r^16
0
Subsegments
20
Back Face (2)
Coat/Scatter
Profile:
Object Explorer

Fig. 12