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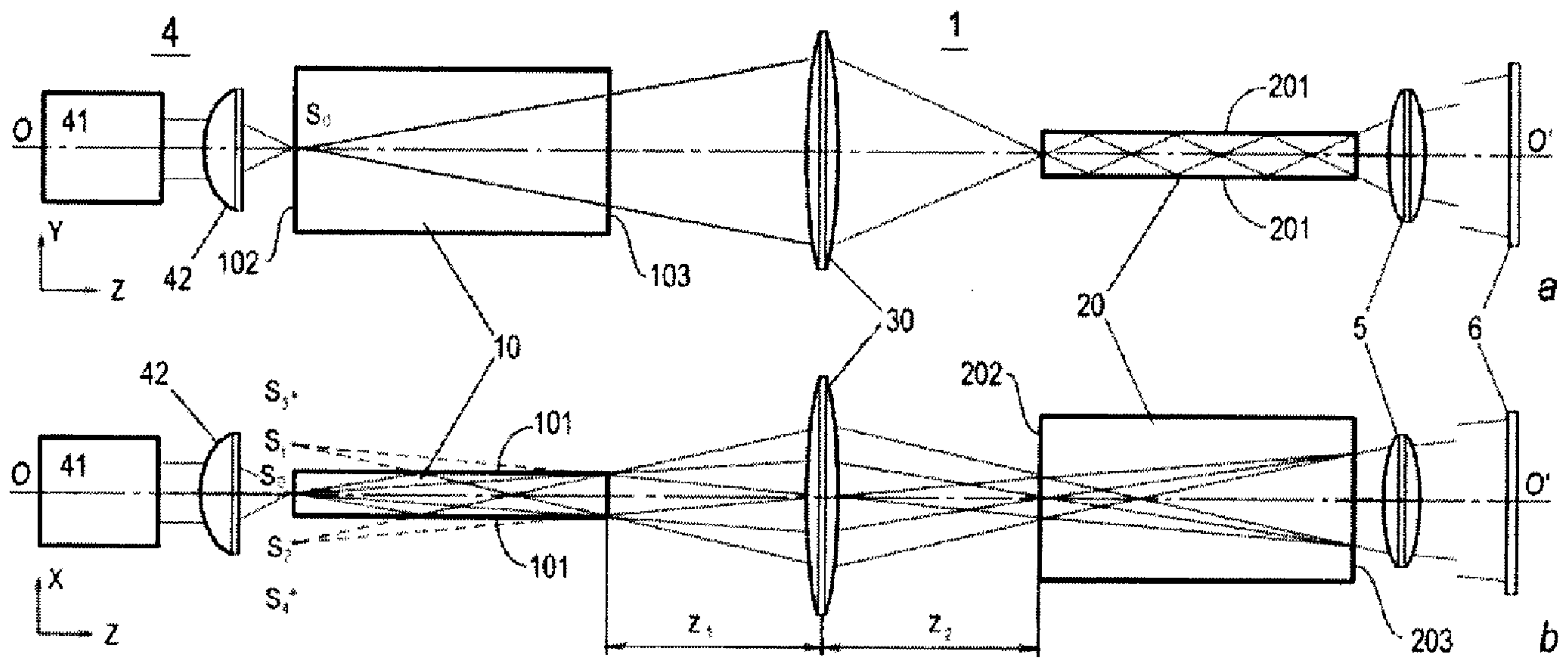


(57) Abrégé/Abstract:
An illumination device is providing a flat top rectangular illumination beam exhibiting a substantially uniform transversal intensity distribution and a specified numerical aperture. A collimated or diverging light beam having a possibly non-uniform transversal intensity distribution is transformed into a rectangular, substantially uniform flat top light beam by homogenizing the light beam with

(57) Abrégé(suite)/Abstract(continued):
an optical integrator comprising a pair of mutually orthogonal planar light guides and relay optic system that focuses the illumination beam outgoing form the first planar light guide onto a front face of the second planar light guide and images an exit face of the first planar light guide onto a plane of an exit face of the second planar light guide. Said flat top rectangular light pattern at the exit facet of the second planar light guide is relayed onto an illumination target.

# *OPTICAL INTEGRATOR AND ILLUMINATION DEVICE USING THE SAME*

**ABSTRACT**

An illumination device is providing a flat top rectangular illumination beam exhibiting a substantially uniform transversal intensity distribution and a specified numerical aperture. A collimated or diverging light beam having a possibly non-uniform transversal intensity distribution is transformed into a rectangular, substantially uniform flat top light beam by homogenizing the light beam with an optical integrator comprising a pair of mutually orthogonal planar light guides and relay optic system that focuses the illumination beam outgoing form the first planar light guide onto a front face of the second planar light guide and images an exit face of the first planar light guide onto a plane of an exit face of the second planar light guide. Said flat top rectangular light pattern at the exit facet of the second planar light guide is relayed onto an illumination target.

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## *OPTICAL INTEGRATOR AND ILLUMINATION DEVICE USING THE SAME*

### FIELD OF THE INVENTION

This invention relates to light beam illumination systems, and more particularly relates to method and apparatus for producing with a high efficiency flat top rectangular illumination beam exhibiting high uniformity of the transverse intensity distribution and a specified numerical aperture.

### BACKGROUND OF THE INVENTION

Precision illumination systems are used extensively in microscopy, in projection, as well as in the fabrication of microcircuits and electronic circuit boards. The varying demands of applications of illumination system are best served by an illumination system which efficiently produces a light beam of desired technical specifications. Typical variables to be optimized at the target include: a. illumination light wavelength (or wavelength range); b. geometry parameters of the light field shape, e.g. circular, rectangular, etc, and its dimensions; c. having the property of uniform intensity distribution across the illumination field; and d. having a desired, usually rather low, numerical aperture (NA) of illumination. Numerical aperture or NA of a converging and/or diverging light beam is the sine of the half-angle of the beam cone multiplied by a refractive index of the medium.

An approach of the prior art is to use some efficient source of light, such as a laser or an arc lamp with collimating optics, as a primary light source. This typically produces a collimated light beam having non-uniform profile, which in most cases has Gaussian, parabolic or cosine beam profile. From these profiles only a small portion of the beam has a low variation intensity distribution illumination which is useful in imaging. In another approach of the prior art, a diffuser plate etched to a degree of roughness is used to provide the desired uniformity property. A major disadvantage of such systems is lacking in delivered light use efficiency.

Another approach of the prior art, disclosed in detail in US Pat. 2186123, for example, is to use fly's-eye lenses to provide the uniformity property to the beam. The fly's-eye lens is a two dimensional array of lenslets assembled into a single optical element and used to spatially transform light from a non-uniform distribution light source to an uniform irradiance distribution at an illumination plane. However this approach cannot be used to provide flat top illumination beams with NA below 0.01; the beam profile is very sensitive to small variations in the mutual positional and angular alignments of the lenslet arrays, laser, and other components; and much of the available light is lost during the mixing process.

An alternative approach of the prior art, disclosed, for example, in US Pat. 5059013 and US Pat. 6205271 presented in Fig. 13). This approach is to use optical integrator rods to provide the uniformity property to the beam. An optical integrator rod is a hollow mirrored, or solid totally internally reflective "light pipe"



CA 3017188 2018-09-12

which uses multiple reflections of a focused light source by reflecting faces to obtain homogenization of round or irregular patterns of illumination and convert them into a flat top rectangular pattern. The rod exit face serves as an object plane for a relay lens system, which reproduces the transverse distribution of light at the exit face onto an illumination target. Thus, the optical integrator rod is used to improve uniformity and efficiently match the aspect ratio of the illumination source to the target. However, chamfers and glass chips on long side corners of the optical integrator rod are known to cause image shadow artifacts in the illumination pattern, especially in the case of usage of so called 'point' light sources, for example, focal spots of laser radiation. Such a cross-shaped shadow of non-chamfered corners as well as chip shadows are clearly visible on the transverse light distribution map of FIG. 14. Besides, a chamfer on the edges of the exit facet of the glass rod or a rectangular aperture plate for masking exit facet edge chips, if the chamfer is absent, restricts some of the illumination. This figure often amounts to about 10% and more of the useable light. The integrator rod is typically made sufficiently long to produce a resulting rectangular light beam of desired specs. Illumination systems for spinning disk confocal microscopy, for example, must project a flat top rectangular illumination beam, having a very low NA ~ 0.004 (US Pat. 2011/0134519), onto a relatively small target about 8mm x 8mm. The solid integrator rod should be too much long and should have very frail design:length should be , for example, more than 150 cm for a rod cross section - 2mm x 2mm.

**SUMMARY OF THE INVENTION**

A number of disadvantages and drawbacks are inherent in illumination systems comprising one of the two basic types of reflective integrators. The present invention is intended to solve the aforementioned problems. The major objective of the present invention is a provision of a method of transformation of non-uniform beam of illumination radiation, e.g. laser light, into a flat top rectangular illumination beam exhibiting high uniformity of the transverse intensity distribution and a specified numerical aperture.

Another objective of the present invention is a provision of an illumination device capable to provide in an object plane an illumination field that has a selected rectangular cross-section of desired dimensions, flat top transverse intensity distribution of high uniformity, and a specified numerical aperture.

Yet another objective of the present invention is provision of reflective type optical integrators whereby an illumination light beam having a non-uniform transverse intensity distribution may be transformed into a flat top light beam having a substantially uniform transverse intensity distribution by shaping and homogenizing the light beam.

It is also objective of this invention to provide a homogenized flat top illumination radiation beam without creating any artifact patterns.

These and further objectives have been achieved by the present invention in which a light beam having a possibly non-uniform spatial intensity distribution is transformed into a flat top illumination light beam having a substantially uniform transverse intensity distribution by homogenizing the light beam with two mutually orthogonal planar light guides (a transparent light passageway having two flat internally reflective surfaces). The first planar light guide performs homogenizing transverse light beam distribution along the first axis orthogonal to its reflecting side surfaces, the second planar light guide serves to homogenize light beam along a second axis orthogonal to the first one and to its own reflecting surfaces. Relay optics, positioned on the device's optical axis, focuses light outgoing from the exit face of the first planar light guide onto an entrance face of the second planar light guide and images said exit face of the first planar light guide onto an exit face of the second planar light guide). Joint operation of sad optical components performs conversion of the non-uniform illumination pattern provided by the illumination unit to a uniform flat top rectangular pattern at the exit face of the second planar light guide. The last is relayed further to an illumination target, where provides a highly uniform rectangular illumination pattern with a predetermined numerical aperture. The illumination pattern has no artifact shadows inherent in the integrator rods, because the method eliminates their origins.

Furthermore, a number of exemplary embodiments of the illumination device and of a respective optical integrator, which realize the method, are provided. They are seen as simple, cost effective instruments that provide high optical efficiency light homogenizing via optical integration. The homogenizer proposed may be used for the entire UV-visible-NIR wavelength range. The invented illumination device design makes it easy handling the integrator components and mounting them without risk of damaging optical surfaces. Another advantage of this device is that the beam profile is less sensitive to variations in the positional alignment of the light source and optical components. The new high uniformity flat top illumination technique can be integrated into various systems developed for different applications such as a spinning disk confocal microscope and/or fluorescent optical microscope to obtain high quality fluorescence images, into digital and analog projection systems, as well as into photolithography machines for production of integrated circuit chips and electronic circuit boards.

Other features and advantages of the present invention will become apparent to those skilled in the art upon examination of the following drawings and the detailed description, and in part will be obvious from the description, or may be learned by practice of the invention. It is intended that all such additional features and advantages be included herein within the scope of the present invention, as defined by the claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments according to the present invention will now be described hereinafter with reference to the accompanying drawings, where like reference numerals designate similar or identical features throughout the several views. In addition to the major optical members there may be shown in the drawings optical axis of the device, chief and/or marginal rays of an illumination light beam; input and output light beams may be illustrates by bold arrows.

It will be appreciated that for the simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale, emphasis instead being placed upon clearly illustrating the principles of the present invention. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity purposes.

FIGS. 1a and 1b, depict simplified schematic YZ and XZ views, respectively, of the first exemplary embodiment of an illumination device in accordance with the present invention.

Fig. 2 depicts schematically the transformation of the illumination light beam in a process of light beam travel through the optical integrator of FIG. 1.

FIG. 3 depicts schematic perspective views of alternative exemplary embodiments of planar light guides for the optical integrator according to the present invention: a rectangular glass slab (***a***); a glass 'sandwich' (***b***): a hollow planar light guide (***c***); a wedge-shaped glass slab (***d***).

FIGS. 4, 5, are pictorial schematic views of alternative exemplary embodiments of the illumination device according the present invention.

FIG. 6 illustrates the transformation of the illumination light beam in a process of light beam travel through the optical integrator of FIG. 5.

FIG. 7 is a perspective view of alternative exemplary embodiment of the optical integrator according the present invention.

FIG. 8 depicts a schematic configuration of another exemplary embodiment of the optical integrator according the present invention comprising two image relaying planar light guides.

FIGS. 9, 10, and 11 depict simplified schematic diagrams of yet other exemplary embodiments of the optical integrator, comprising image relaying gradient index (GRIN) planar light guides.

FIG. 12 presents pictorial schematic views of yet another alternative exemplary embodiment of a image relaying planar light guide (a) and of the optical integrator (b) using the same.

Fig. 13 is a schematic showing an example of an integration rod homogenizing system. Prior art.



CA 3017188 2018-09-12

Fig. 14 depicts a map of transverse light distribution across an exit face of an integration rod of a light homogenizer exibiting shadow artifacts. Prior art.

**DETAILED DESCRIPTION OF THE INVENTION**

All the exemplary embodiments disclosed hereinafter contain an optical integrator assembly comprising two mutually orthogonal single-axis optical integrator elements in the form of planar light guides. For the sake of definiteness and clarity, the axis orthogonal to reflecting planes of the first planar light guide is denoted as X-axis while the axis orthogonal the reflecting sides of the second planar light guide is denoted as Y-axis, a direction of light propagation is denoted as Z-axis coinciding with an optical axis of the illumination device. The first and the second single-axis optical integrator elements are called hereinafter "X-integrator" and "Y-integrator", respectively. However, the invention is not intended to be limited to the specific coordinate system selected, and it is to be understood that any other specific system of coordinate may be used.

In descriptions of exemplary embodiments of the present invention illustrated in the drawings, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology selected, and it is to be understood that each specific element includes all technical equivalents that operate in a similar manner to accomplish a similar purpose. The terms "light" and "radiation" may be used interchangeably and refer to radiation in the UV-visible-IR spectral range. The term "light source" and "radiation source" may refer to any source able to generate and emit radiation having a characteristic spectrum and spatial distribution,.

FIG. 1 depicts simplified schematic YZ and XZ views (a and b, respectively) of the first exemplary embodiment of an illumination device comprising an optical integrator in accordance with the present invention. The entire assembly of the proposed embodiment preferably comprises: an illumination unit 4; optical integrator assembly 1; a projection lens system 5, and a target 6.

Said Illumination unit 4, providing nearby an entrance facet 102 of said X-integrator10 a point-like light source emitting a diverging beam of illumination radiation, characterized by the light beam numerical aperture (NA), is schematically shown, for example, in the form of a laser source 41 with a focusing lens 42. Alternatively, said illumination module capable to provide a point-like luminous light spot may be implemented in a variety forms including but not limited to lasers with fiber optic cable, super-continua fiber sources, LEDs and super luminescent diodes with focusing optics, gas discharge lamps with focusing reflective optics, or any other suitable radiation sources as would be apparent to someone skilled in the art.

Said optical integrator assembly 1 comprises two mutually orthogonal single-axis optical integrating elements: X-integrator 10 and Y-integrator 20 turned around an optical axis of the device orthogonally to said X-integrator and relay optics, schematically presented, for example, in the form of a single bi-convex lens 30 with its focal distance $F_{30}$. Said X-integrator 10 may be, for example, a rectangular glass slab, of predetermined length $L_1$, thickness $t_1$, and width $w_1$. It has two opposing mutually parallel internally reflecting facets 101, 101', oriented orthogonally to X-axis, an entrance facet 102,an exit facet 103, and two non-optical side facets 104, 104' as depicted in FIG. 3a. Material of said glass slab is transparent for the illumination radiation and has a refractive index $n_1$. Said Y-integrator 20 is a similar rectangular glass slab having equal or differing design parameters: length $L_2$, thickness $t_2$, width $w_2$, and a glass refractive index $n_2$. It has two opposing mutually parallel internally reflecting facets 201, 201', oriented orthogonally to Y-axis, entrance and exit facets 202, 203, and non-optical side facets 204, 204'. Each of said glass slabs 10, 20 operates as a planar light guide, that is light may travel in it in the direction parallel to the corresponding facets 101, 101' or 201, 201' being confined in it by total internal reflection, Each of said planar light guides 10, 20 performs functions of single-axis homogenizing transverse light distribution along the axis orthogonal to the corresponding reflecting facets 101, 101' and 201, 201'.

Lengths $L_1$ $L_2$ and distances between reflecting surfaces or thicknesses $t_1$, $t_2$ of said glass slabs 10, 20 have to satisfy the following condition:

$$L_{1,2} \geq \frac{t_{1,2} \cdot n_{1,2} \cdot k_{1,2}}{NA_{1,2}}; \qquad (1)$$

Here: subscripts 1, 2 relate to the X-integrator and to the Y-integrator, respectively, $n_1 > 1$ and $n_2 > 1$ are refractive indexes of the slab glass material; $NA_1$and $NA_2$ are numerical apertures of the corresponding input radiation beams, e.g. $NA_1 = NA_0$, where $NA_0$ is the numerical aperture of the beam provided by the illumination unit 4; $k_1 > 1$, $k_2 > 1$ are minimal desired numbers of reflections of marginal rays of the radiation beam from facets 101, 101' and 201, 201' of said glass slabs 10, 20, respectively. The values $k_1$ *and* $k_2$ are defined by a grade of non-uniformity of illumination pattern provided by the illumination unit 4 and by desired uniformity of a light distribution on the target 6

Widths $w_1$ and $w_2$ of the glass slabs 10, 20 must be large enough to eliminate any contact of the propagating light rays with non-optical narrow sides 104, 104' and 204, 204':

$$w_{1,2} > \frac{2NA_{1,2} \cdot L_{1,2}}{n_{1,2}} = 2t_{1,2} \cdot k_{1,2} \qquad (2)$$

For the sake of simplicity said projection lens system 5 is shown only schematically as a single bi-convex lens, it may be implemented in a variety of forms, previously developed for illumination applications.

All said members 4, 10, 30, 20, 5, and 6 in the embodiment of FIG. 1 are arranged along the optical axis OO' of the illumination device and symmetrically relative to it, so that X-integrator reflecting facets 101, 101' are perpendicular to the XZ-plane and said Y-integrator reflecting facets 201, 201' are perpendicular to YZ-plane. Said imaging lens 30 is positioned downstream at a predetermined distance $z_1$ from said X-integrator facet 103; said Y-integrator 20 is positioned downstream at a distance $z_2$ form said imaging lens 30 so that its entrance and exit facets 202, 203 reside in image planes conjugate to corresponding planes of said entrance and exit facets 102, 103 of said X-integrator 10. Said exit facet 203 serves as the optical integrator exit plane, relayed by said projection lens 5 onto said target 6.

Operation of the optical integrator assembly of FIG. 1 is illustrated with FIG. 2 that presents transversal intensity distributions of the illumination light beam at the entrance (a) and exit (b) facets of said X-integrator 10 and at the entrance (c) and exit (d) facets of said Y-integrator 20. An illumination beam from said illumination unit 4 may originally have a circular highly non-uniform profile providing at said X-integrator entrance facet 102 a transversal distribution $S_0$ of FIG. 2a. Said light beam is repeatedly internally reflected by the facets 101, 101' of said X-integrator 10 to become homogenized (mixed) along the axis 'X' (FIG. 2b). Said relay optics 3 relays the original light spot $S_0$ and its multiple reflections $S_j$ (j = 1, 2, 3, 4 for $k_1$ = 2, for example) from a plane of said X-integrator entrance facet 102 to the conjugate Y-integrator entrance facet 202 with a magnification $m_1 = z_2/(L_1 + z_1.)$, thus providing a set of corresponding light spots $S'_0$, $S'_j$ (FIG. 2c), and relays said light distribution of FIG. 2b, from said X-integrator exit facet 103 to a conjugate plane of the exit facet 203 of said Y-integrator 20 with a magnification $m_2 = (L_2 + z_2)/z_1 > m_1$ Light entering said Y-integrator 20 via its facet 202 is repeatedly internally reflected by the facets 201, 201' to become homogenized along the axis 'Y', thus providing at said Y-integrator exit facet 203 a flat top rectangular light pattern (FIG. 2d) with an aspect ratio

$$A = \frac{t_1 \cdot m_2}{t_2}. \qquad (3)$$

Its numerical apertures in the XZ and YZ planes, respectively, are:

$$NA_X = NA_0/m_1 > NA_Y = NA_0/m_2 \qquad (4)$$

The light pattern is relayed with said projection lens system 5 from said Y-integrator exit facet 203 to said illumination target 6 to provide there a magnified flat top rectangular illumination pattern with a pre-determined NA, exhibiting essential uniformity and high edge steepness.

It should be noted that focusing lens 42 may be a positive cylindrical lens, whose cylinder axis lies in the YZ plane, and distance $z_2$ between said relay lens 30 and said Y-integrator front facet 202 is close to a focal length of said lens 30. Said relay lens 30 projects a focal line, oriented along X-axis, onto said Y-integrator entrance facet 202 and relays an illumination pattern from said X-integrator exit facet 103 to a plane of said Y-integrator exit facet 203 as explained hereinabove.

Said X-integrator 10 and Y-integrator 20 or planar light guides are described herein as "glass slabs". This is for sake of brevity and clarity only; they may be planar light guides, implemented in a plurality of alternative forms, some examples are depicted in FIG. 3. Although all the numerals and explanations in FIG. 3 are referred to the X- integrator hereinafter, they pertain equally to the Y-integrator.

FIG. 3a is a schematic perspective view of the discussed hereinabove first example of said planar light guide 10 built in the form of a rectangular glass slab with two opposing mutually parallel internally reflecting facets 101, 101' and entrance and exit facets 102, 103 orthogonal to said reflecting facets 101, 101'. Said side facets 104, 104' of the embodiment may be of any optical quality and any shape, but providing non-disturbed light propagation in said planar light guide.

FIG. 3b is a schematic perspective view of an alternative example of said planar light guide 10, which is a sandwich planar light guide comprising at least three flat layers 105, 106, 106' of glass materials with different refractive indexes having mutually parallel interfaces, extending in the directions parallel to their interfaces. This operates as planar light guide only if the refractive index of the middle or core layer 105 is larger than that of the surrounding clad layers 106, 106', so that light may be confined in the middle layer 105 by total internal reflection. Co-joint polishing of said front and back faces 102, 103 makes it possible to manufacture the planar light guide without chips and chamfers on the core-clad division, and to solve therewith the problem of decreased optical integrator efficiency as a result of use of a masking aperture or chamfering.

FIG. 3c is a perspective view of another alternative example of said planar light guide 10, which is a hollow or mirror slot planar light guide comprising a pair of highly reflecting mirrors 107 and 107' with their inward facing mirrored surfaces 108, 108' being fixed mutually parallel at a predetermined distance $t_1$ between them with, for example, of two spacers 109, 109'. A length $L_1$, a width $w_1$ of, and the distance $t_1$ between the mirrored surfaces of the planar light guide 10 are defined by the same equations (1), (2), where the refractive index $n_1 = 1$.

FIG. 3d is a perspective view of yet another alternative example of said planar light guides 10, 20 implemented in the form of wedge-shaped glass slabs of a diverging, $T > t$ as depicted or of a converging configuration. Alternatively, said wedge-shaped planar light guide may have at least one reflecting facet, which is non-planar, but rather curved one having a gradually changing angle with Z-axis. It should be clear for one skilled in the art that wedge-shaped planar light guides may be alternatively implemented in the form of diverging or converging planar light guides, similar to those depicted in FIGS. 3b, 3c.

It should be noted that, alternatively, at least one of facets 102, 103 of said planar light guides of FIGS. 3a, 3b, and 3d may be not orthogonal to optical axis of said glass slab 10, thus providing an optional folding of the illumination device optical axis. Furthermore, the device optical axis may be folded within the planar light guides of FIGS. 3a – 3c by providing said planar light guides with additional internally reflecting surfaces or mirrors, depending on its design.

Optical material of said planar light guides 10, 20 is described herein as "glass". This is for sake of brevity and clarity only; it may refer to any plurality of optical materials transparent in specified spectral ranges including, but not limited to mineral or polymer glass, optical ceramics, mono- and polycrystalline semiconductor material,, as it would be apparent to someone skilled in the art.

FIGS. 4a and 4b depict simplified schematic XZ and YZ projections, respectively, of another exemplary embodiment of an illumination device in accordance with the present invention; . The entire assembly of the proposed embodiment is similar in general to one of FIG. 1, and comprises the same major optical components: an illumination unit 4, schematically presented in the form of a laser 41 with a fiber optic cable 43, the mutually orthogonal X-integrator 10 and Y-integrator 20, a projection lens 5, and a target 6 (not shown); but relay optics 3 is rather comprising two positive lenses 31 and 32 separated one another for a distance $z_3 > z_1, z_2$, and providing predetermined magnifications $m_1$ *and* $m_2$. FIG. 4***c*** is a perspective view of said optical integrator assembly 1comprised

The proposed embodiment is operating in the same manner as one of FIG. 1, illustrated by FIG. 2, i.e. transforms non-uniform beam of illumination radiation into a flat top rectangular illumination beam exhibiting high uniformity of the transverse intensity distribution with an aspect ratio $A$ and numerical apertures $NA_X$ and $NA_Y$ governed by the same formulas (3) and (4) respectively.

In one example, said X-integrator 10 and Y-integrator 20 in the embodiment of FIG. 4 may be built with the same glass with a refractive index $n$, and have equal lengths $L$ and lenses 31, 32 may have equal focal lengths $F = L/2n$. Said distances $z_1$ and $z_2$ may be much less than said separation distance $z_3 \approx 2F$. In the case, the magnification $m_1 = 1$is provided mainly by said lens 31, while the magnification $m_2 = 1$is provided mainly by said lens 32. The flat top rectangular light pattern at said Y-integrator exit facet 203 has an aspect ratio $A = t_1 : t_2$; numerical apertures of the exit light beam are $NA_X = NA_Y = NA_0$.

An example of implementation of the illumination device of Fig. 4 is an illumination system for a spinning disk confocal microscope for fluorescent imaging of biological specimens. Typical specifications of the microscope illumination system are (US Pat. 2011/0134519): illumination field at the microlens spinning disk plane, i.e. target size, is 8 mm x 8 mm, a light beam numerical aperture at the target 6 must be $NA_{IL} = NA_X = NA_Y \leq 0.004$,. Major design parameters of such illumination system are: a collimated beam of excitation radiation, provided by the laser 41 and having a diameter d = 1.6 mm is to be focused with said lens 42 having focal distance $F_{42}$ = 12.5 mm to provide a luminous spot with $NA_0$ = 0.064; glass slab lengths $L_1 = L_2 = 35$ mm, thicknesses $t_1 = t_2$ = 0.5 mm , widths $w_1 = w_2 \geq 3$ mm, and indexes of refraction $n_1 = n_2 = 1.52$; relay optics comprises a pair of lenses with focal lengths $F_{31} = F_{32}$ = 15 mm; distances $z_1$ =

$z_3$ = 3.5 mm, $z_2 = 2F$ = 30 mm; exit numerical aperture of the optical integrator $NA = NA_0$ = 0.064. A projection lens 5 must provide magnification $m_5$ = 16 and, consequently, the desired NA ≤ 0.004.

It should be noted that the multi-component relay optics 3 may be an astigmatic relay system i.e. at least one lens of the system may be a cylinder lens. FIG. 5 is a perspective view of an exemplary embodiment of said optical integrator assembly 1 with astigmatic relay optics 3. The entire assembly of the of the optical integrator 1 is similar, in general, to one of embodiment of FIG. 4, and comprises said mutually orthogonal X-integrator 10 and Y-integrator 20, and relay optics 3 rather comprising two crossed cylindrical lenses 33 and 34 having focal lengths $F_{33}$ and $F_{34}$, respectively, and similarly separated one another for a distance $z_3$. A cylinder axis of said lens 34 lies in a plane XZ, orthogonal to said X-integrator reflecting planes 101, 101', while a cylinder axis of said lens 35 lies in a plane XZ, orthogonal to said Y-integrator reflecting planes 201, 201'.

FIG. 6 illustrates the transformation of the illumination light beam traveling through the optical integrator of FIG. 5. There are presented transversal distributions of said light beam at said entrance (a) and exit (b) facets of said X-integrator 10 and at said entrance (c) and exit (d) facets of said Y-integrator 20. The distributions of FIGS. 6a, 6b, and 6d are identical to corresponding distributions of FIG. 2. The line-shaped distribution of the FIG. 6c is a sum of overlaid astigmatic light projections of the original illumination spot $S_0$ and of said virtual light spots $S_j$ provided by said cylindrical lens 34. A length of the luminous line is defined by the light beam divergence; its width is equal to a magnified diameter of the original illumination spot $S_0$. Said cylindrical lens 35 provides an astigmatic projection of said X-integrator exit facet 103 onto a plane of said Y-integrator exit facet 203. Light entering said Y-integrator 20 is repeatedly internally reflected by the facets 201, 201' to become homogenized along the axis 'Y', thus providing a flat top rectangular light pattern of FIG. 6d with an aspect ratio $A$ and numerical apertures $NA_X$, $NA_Y$ governed by equations (3), (4) respectively, where magnifications $m_1$ and $m_2$ are defined by the corresponding cylindrical lenses 33 and 34.

In one example, said X-integrator 10 and Y-integrator 20 in the embodiment of FIG. 5 may be built with the same glass, may have the same lengths $L$, and cylindrical lenses 33, 34 may have the same focal lengths $F$ and may be positioned at equal distances $z_1 = z_3 = 2F - L/n$ from corresponding planar light guides 10, 20. In the case, the aspect ratio of said exit light pattern is $A = t_1 : t_2$; numerical apertures are $NA_X \approx NA_Y \approx NA_0$.

It should be noted that a small shift $\Delta z << F$ of said lens 32 in the embodiment of FIG. 4 and/or lens 34 in the embodiment of FIG. 5 along Z-axis results in a variation of the magnification value $m_2$ and provides a capability of varying the illumination pattern aspect ratio $A$:

$$A = \frac{t_1}{t_2}(1 - \Delta z/F).$$

All the lenses are schematically presented in the FIGS. 1, 4, 5 in the form of spherical or cylindrical singlet lenses. This is for sake of brevity and clarity only; this may or may not be the case. It may refer to any plurality of focusing elements including but not limited to spherical and cylindrical singlet lenses, aspheric and acylinder singlet lenses, gradient index lenses, multicomponent lenses, Fresnel and diffractive lenses, or any other focusing elements, including reflective focusing, elements. FIG. 7 depicts, for example, a perspective view of an alternative exemplary embodiment of the optical integrator assembly 1 comprising two-component relay optics in the form of two concave spherical or cylindrical focusing mirrors 35, 36.

The glass slabs 10, 20 and corresponding nearest optical members (i.e. lenses 31, 32 in the arrangement of FIG. 4 and cylindrical lenses 33, 34 in the arrangement of FIG. 5) may be replaced by single pieces of glass 11, 21 as for example, shown in FIG. 8, thereby eliminating two glass-to-air transitions and two air-to-glass transitions within the optical integrator. Corresponding convex spherical or cylindrical surfaces may be an exit surface 113 of said X-integrator 11 and an entrance surface 212 of said Y- integrator 21. The planar light guides 11, 21 may perform not only integration functions, but image relay functions as well. The optical integrator of FIG. 8 is operating in the same manner as corresponding exemplary embodiments of FIGS. 4, 5, illustrated by corresponding FIGS. 2, 6.

FIG. 9 depicts schematic YZ (a) and XZ (b) projections of yet another exemplary embodiment of the optical integrator 1 according the present invention. The entire assembly comprises mutually orthogonal X-integrator 12 and Y-integrator 22 of corresponding lengths $L_{12}$, $L_{22}$ and thicknesses $t_{12}$, $t_{22}$, both implemented in the form of planar gradient index (GRIN) lenses with radial refraction gradients. Gradient-index optics is the branch of optics employing optical effects produced by a gradient of the refractive index of a material. Such gradual variation can be used to produce lenses with flat back and front surfaces. Said integrating planar light guides 12, 22 which are radial GRIN lenses, have quadratic transversal index profiles:

$$n(r) = n_0\left(1 - \frac{\alpha^2}{2} r^2\right) \qquad (5)$$

Where α is a gradient constant that may be taken equal for both GRIN planar light guides 12, 22 without loss of generality, $r^2 = x^2 + y^2$, point $r = 0$ corresponds to the optical axis of the GRIN lens. The index profile will cause rays entering one face of the rod to follow sinusoidal paths of the form $r = r_0 \sin(\alpha r)$, where the amplitude, $r_0$ is related to the angle of incidence at the axis of the rod by $\tan(\theta) = \alpha r_0$. GRIN lenses are characterized by their 'pitch length', $p = 2\pi/\alpha$. The pitch length is the number of cycles that light will make in the given length of the GRIN glass slab. GRIN planar light guides 12, 22 will act as image relays, when their lengths $L_{12}$ and $L_{22}$ satisfy the following conditions:

$$L_i = p(N_i/2 - \delta); \qquad (6)$$

$$0 < \delta < \frac{1}{4}, \qquad (7)$$

where $l$ = 12, 22 relates to corresponding GRIN glass slabs and N = 0, 1, 2, 3... is a natural number. The parameter $\delta$ must have close values for both GRIN planar light guides 12, 22. A distance z from an exit facet 123 of said GRIN X-integrator 12 to an entrance facet 222 of sad GRIN Y-integrator 22, positioned downstream is:

$$z = \frac{1}{\propto n_0} \tan\{\pi(1 - 2\delta)\} \qquad (8)$$

Said optical integrator of FIG. 9 operates similarly to the optical integrator 1 of FIG. 4, but image relay functions are provided by said GRIN planar light guides 12, 22.

FIG. 10 depicts schematic YZ (a) and XZ (b) projections of an alternative exemplary embodiment of the optical integrator 1 comprising mutually orthogonal X-integrator 13 and Y-integrator 23, implemented in the form of single-axis GRIN glass slabs, operating as cylindrical lenses with their refraction gradients oriented along Y- axis and along X-axis, respectively. Said GRIN planar light guides 13, 23 have similar quadratic index profiles (5), wherein r = y and r = x, respectively. Both llengths $L_{13}$ and $L_{23}$ of said GRIN planar light guides 13, 23 and distance $z$ between them have to satisfy the same condition (6) (8), but with differing requirements for parameter $\delta$ close or equal for both single axis GRIN planar light guides:

$$0 \le \delta_X \approx \delta_Y < 1/4, \qquad (9)$$

The optical integrator of FIG. 10 operates similarly to the exemplary embodiment of FIG. 5, but astigmatic focusing functions are provided by said single-axis GRIN planar light guides 13, 23.

FIG. 11 is a perspective view of an example of the illumination device comprises GRIN planar light guides 13, 23, whose parameters $\delta_X \approx \delta_Y = 0$. The exit facet 133 of said GRIN X-integrator 13 is to be close-spaced from or to be in a contact with the entrance facet 232 of said GRIN Y-integrator 23. In the example of FIG. 11 said cylindrical GRIN relays 13, 23 are characterized by unit value magnifications: $m_1 = m_2 = 1$. A resulting flat top rectangular pattern at said exit facet 233 has an aspect ratio $A = t_{13} : t_{23}$ and numerical apertures equal to one of the illumination unit 4: $NA_X = NA_Y = NA_0$.

It should be noted that that single-axis optical integrators comprised in the embodiments of FIGS. 4, 5, 7 – 11 may be implemented in the form of multilayer 'sandwich' planar light guides similar to one of FIG. 3b and/or in the form of wedge-shaped glass slabs of the diverging or converging configuration, illustrated by FIG 3d as would be apparent for someone skilled in the art.

Alternatively, optical integrating planar light guides may have internal components or design features exhibiting properties of refractive and/or reflective image relaying optical members as, for example, planar light guides presented in FIG 12, where OO' is an input optical axis and O'O" is a folded exit optical axis. FIG. 12a presents a top view of such an image relaying X-integrator 14 (or Y-integrator 24), which may be a glass slab with two opposing mutually parallel internally reflecting facets 141, 141', entrance facet 142, exit facet 143, mirrored cylindrical surface 145 with the cylinder axis orthogonal to said reflecting facets 141, 141', and two non-optical facets 144, 144'. When sum of distances $l_1$ and $l_2$ is close to the doubled radius R of the cylindrical mirrored surface 145, the last acts as an astigmatic relay, i.e. provides an astigmatic projection of a light spot from the entrance facet 142 onto exit facet 143. FIG. 12b is a schematic perspective view of the optical integrator assembly1, comprising identical mutually orthogonal X-integrator 14 and Y-integrator 24 implemented in the form of relaying planar light guides of FIG. 12a.

The proposed hereinbefore exemplary embodiments may comprise additional optical members such as, for example, lenses, and focusing and folding mirrors, retarder plates, bandpass filters for multi-spectral illumination, light modulators, choppers, phase randomizers in the form of spinning light diffusers, or other optical elments as would be apparent to someone skilled in the art.

It should be noted that the specific exemplary embodiments has been particularly shown and described heretofore only for the purpose of explaining and illustrating the present invention. It will therefore be apparent to those skilled in the art that various changes, modifications or alterations to the invention as described herein, may be made without departing from the spirit and scope of the invention and essential characteristics thereof. Furthermore, although the preferred application field of the present invention, as set forth herein, is fluorescent and spinning disk confocal optical microscopy, other general illumination applications are contemplated. All such embodiments and variations are believed to be within the sphere and scope of the invention as defined by the claims appended hereto.

Dr. Peter A. Vokhmin

Date: September 12, 2018

## *OPTICAL INTEGRATOR AND ILLUMINATION DEVICE USING THE SAME*

**CLAIMS**

What is claimed is

**1.** An illumination device comprising:

an illumination unit providing a point-like luminous spot operating as a source of a diverging beam of illumination radiation;

an optical integrator assembly comprising:

two mutually orthogonal planar light guides disposed along an optical axis of the illumination device, namely: a first planar light guide having two opposing internally reflecting planes, an entrance face, and an exit face for homogenizing said light beam along a first transversal direction; a second planar light guide having two opposing internally reflecting planes, an entrance face, and an exit face and turned around said optical axis orthogonally to said first planar light guide for homogenizing said light beam along a second transversal direction, orthogonal to the first one;

a projection lens system:

an illumination target; wherein

sad illumination unit, said optical integrator assembly, said projection lens system, and said illumination target are arranged along said optical axis of the illumination device and symmetrically relative to it.

**2.** The optical illumination device of claim 1, wherein said optical integrator assembly further comprising relay optics, positioned in-between said exit face of said first planar light guide and said entrance face of said second planar light guide.

**3.** The optical illumination device of claim 2, wherein sad first planar light guide and said second planar light guide, having predetermined lengths and widths, are selected from the group comprising

a glass slab of predetermined thickness having two opposing mutually parallel internally reflecting facets, wherein material of said glass slab is substantially transparent for the illumination radiation;

a wedge-shaped glass slab of steadily varying thickness from their entrance to exit facets, wherein material of said glass slab is substantially transparent for the illumination radiation;

a sandwich planar light guide comprising at least three layers of glass materials with different refractive indexes having mutually parallel interfaces, wherein a middle core layer of a predetermined thickness has a refractive index larger than that of the surrounding clad layers and said glass materials are substantially transparent for the illumination radiation;

a sandwich planar light guide comprising at least three layers of glass materials with different refractive indexes, wherein a middle core layer of a steadily varying thickness from their entrance to exit faces has a refractive index larger than that of the surrounding clad layers and said glass materials are substantially transparent for the illumination radiation;

a hollow planar light guide comprising a pair of highly reflecting mirrors with their inward facing mirrored surfaces being fixed mutually parallel at a predetermined distance between them; and

a hollow planar light guide comprising a pair of highly reflecting mirrors with their inward facing mirrored surfaces being fixed at predetermined distances between them steadily varying from their entrance to exit faces.

**4.** The optical illumination device of claim 3, wherein said illumination unit, said first planar light guide, said second planar light guide, and said relay optics are arranged along the optical axis of the illumination device and symmetrically relative to it, so that

a plane of said entrance face of said first planar light guide and a plane of said entrance face of said second planar light guide are conjugate planes;
a plane of said exit face of said first planar light guide and a plane of said exit face of said second planar light guide are conjugate planes.

**5.** An optical illumination device of claim 4, wherein sad relay optics comprises at least one relay lens.

**6.** An optical illumination device of claim 4, wherein sad relay optics comprises at least two lenses:

a first lens positioned close to said exit face of said first planar light guide;
a distant second lens positioned close to said entrance face of said second planar light guide.

**7.** The optical illumination device of claim 6, wherein sad first lens and said second lens are positive spherical lenses.

**8.** The optical illumination device of claim 6, wherein at least one of said first and said second lenses is a positive cylindrical lens, wherein

cylinder axis of said first cylindrical lens lies in a plane perpendicular to the reflecting planes of said first planar light guide;

cylinder axis of said second cylindrical lens lies in a plane perpendicular to the reflecting planes of said second planar light guide.

**9.** The optical illumination device of claim 1, wherein said first planar light guide and said second planar light guide are image relay planar light guides, arranged along the optical axis of the illumination device and symmetrically relative to it, so that

a plane of said entrance face of said first planar light guide and a plane of said entrance face of said second planar light guide are conjugate planes;
a plane of said exit face of said first planar light guide and a plane of said exit face of said second planar light guide are conjugate planes.

**10.** The optical illumination device of claim 1, wherein sad first planar light guide and said second planar light guide, having a predetermined lengths and widths, are selected from the group comprising

a glass slab of predetermined thickness having two opposing mutually parallel internally reflecting facets, wherein material of said glass slab is substantially transparent for the illumination radiation;

a wedge-shaped glass slab of steadily varying thickness from their entrance to exit facets, wherein material of said glass slab is substantially transparent for the illumination radiation;

a sandwich planar light guide comprising at least three layers of glass materials with different refractive indexes having mutually parallel interfaces, wherein a middle core layer of a predetermined thickness has a refractive index larger than that of the surrounding clad layers and said glass materials are substantially transparent for the illumination radiation;

a sandwich planar light guide comprising at least three layers of glass materials with different refractive indexes, wherein a middle core layer of a steadily varying thickness from their entrance to exit faces has a refractive index larger than that of the surrounding clad layers and said glass materials are substantially transparent for the illumination radiation;

**11.** The optical illumination device of claim 10, wherein sad exit face of said first planar light guide and said entrance face said second planar light guide are spherical convex surfaces.

**12.** The optical illumination device of claim 10, wherein sad exit face of said first planar light guide and said entrance face said second planar light guide are cylindrical convex surfaces, wherein

cylinder axis of said exit face of said first planar light guide lies in a plane perpendicular to the reflecting planes of said first planar light guide;

cylinder axis of said entrance face of said second planar light guide lies in a plane perpendicular to the reflecting planes of said second planar light guide. .

**13.** The optical illumination device of claim 10, wherein said wherein said first planar light guide and said second planar light guide are gradient index (GRIN) planar light guides with transversal refraction gradients.

**14.** The optical illumination device according to claim 13, wherein sad GRIN planar light guides have lengths governed by the equation: $L = p(N/2 - \delta)$, wherein

p is a pitch of said GRIN planar light guides;
N = 1, 2, 3... is a natural number; and
$\delta$ is a parameter of said GRIN planar light guides.

**15.** The optical illumination device of claim 14, wherein
said GRIN planar light guides have radial refraction gradients and operate as positive spherical GRIN lenses and
said parameter $\delta$ of said GRIN planar light guides satisfies condition $0 < \delta < 1/4$.

**16.** The optical illumination device of claim 14, wherein
said GRIN planar light guides are single-axis GRIN planar light guides that have refraction gradients, directed along the widths of said GRIN planar light guides and operate as positive cylindrical GRIN lenses and
said parameter $\delta$ of said GRIN planar light guides satisfies condition $0 \leq \delta < 1/4$.

**17.** The optical illumination device of claim 16, wherein

sad parameter $\delta = 0$ and
said exit facet of said first GRIN planar light guide adjoins said entrance facet of said second GRIN planar light guide.

**18.** An illumination method for providing with a high efficiency flat top rectangular illumination beam, exhibiting a substantially uniform transversal intensity distribution and a predetermined numerical aperture, said illumination method comprising steps of:

providing a illumination unit comprising a light source; an optical integrator assembly, comprising a first and a second mutually orthogonal planar light guides, each of which has two opposing internally reflecting planes, an entrance face, and an exit face, and relay optics; a projection lens system; and an illumination target;

providing close to an entrance face of said first planar light guide a point-like source of a diverging light beam having a possibly non-uniform transversal intensity distribution;

directing said light beam into said first planar light guide via its entrance face;

homogenizing the light beam along a first transversal direction due to repetitive internal reflections by the reflecting planes of said fist planar light guide;

focusing the light outgoing from said first planar light guide onto entrance face of said second planar light guide with said relay optics;

relaying image of said exit face of said first planar light guide onto said exit face of said second planar light guide,

homogenizing the light beam along an orthogonal second transversal direction with a second planar light guide, thus providing a flat top rectangular light pattern at the exit face of said second planar light guide;

relaying said flat top rectangular light pattern from said exit face of said second planar light guide to said illumination target with said projection lens system.

**19.** An illumination method of claim 18 wherein

said focusing the light outgoing from said first planar light guide onto entrance face of said second planar light guide is provided by projection with said relay optics of a plane of entrance face of said first planar light guide to said entrance face of said second planar light guide.

Dr. Peter A. Vokhmin

Date: September 12, 2018

## *OPTICAL INTEGRATOR AND ILLUMINATION DEVICE USING THE SAME*

**DRAWINGS**

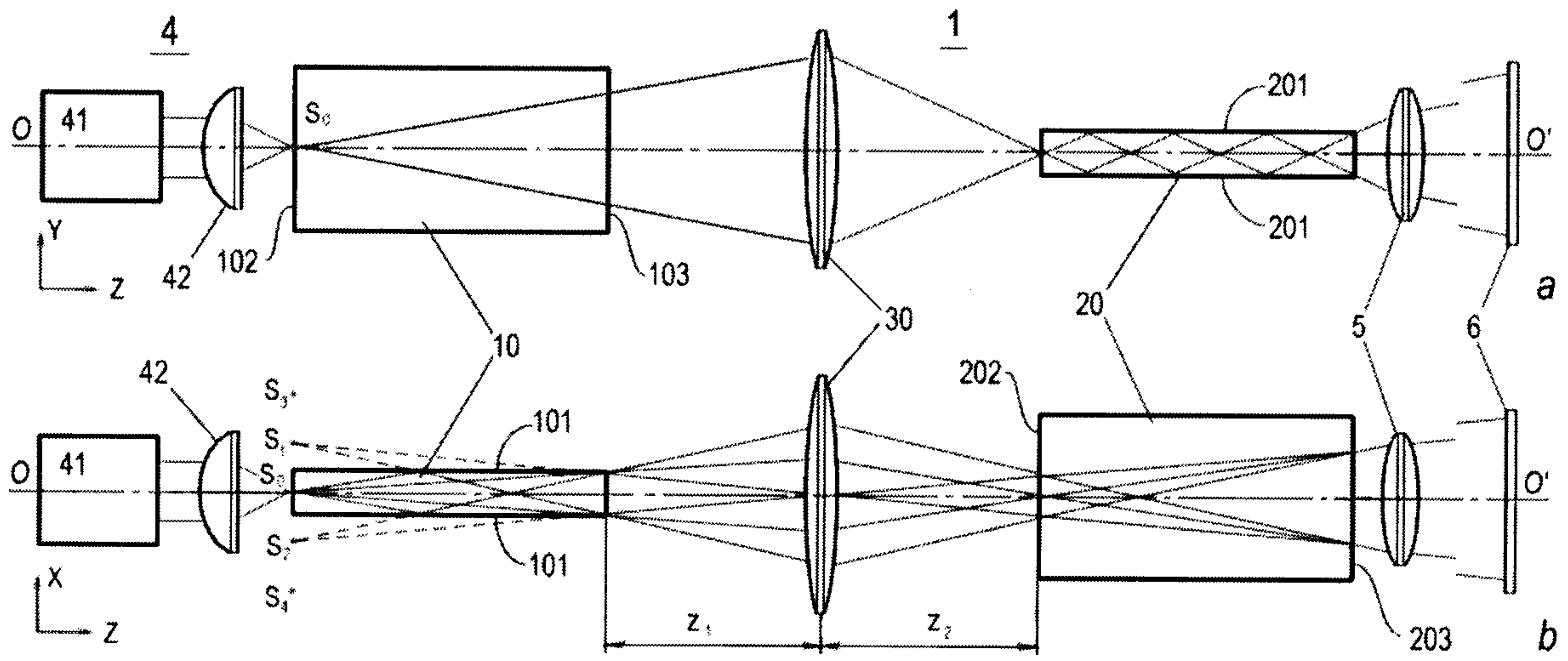


**FIG. 1**

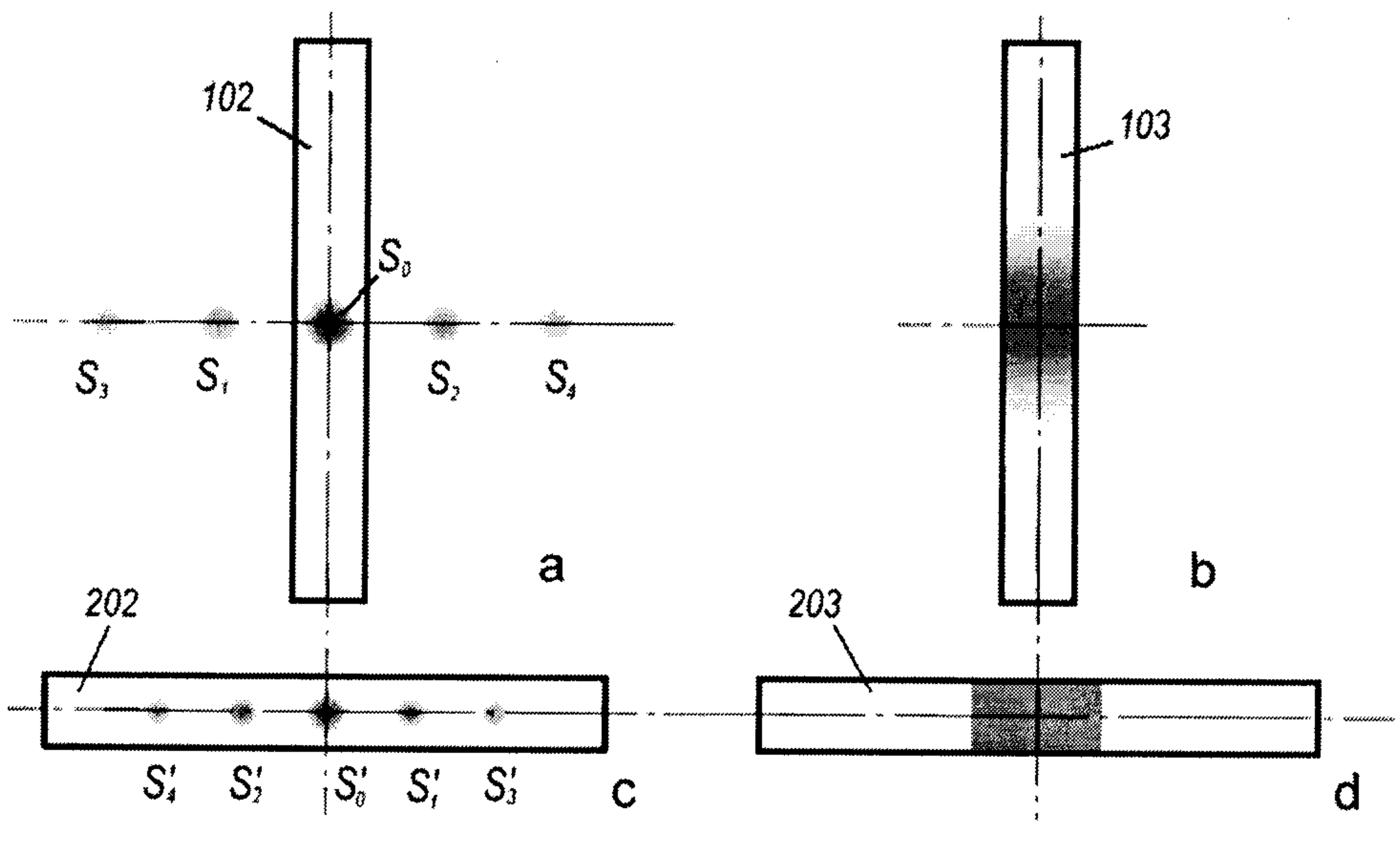


**FIG. 2**



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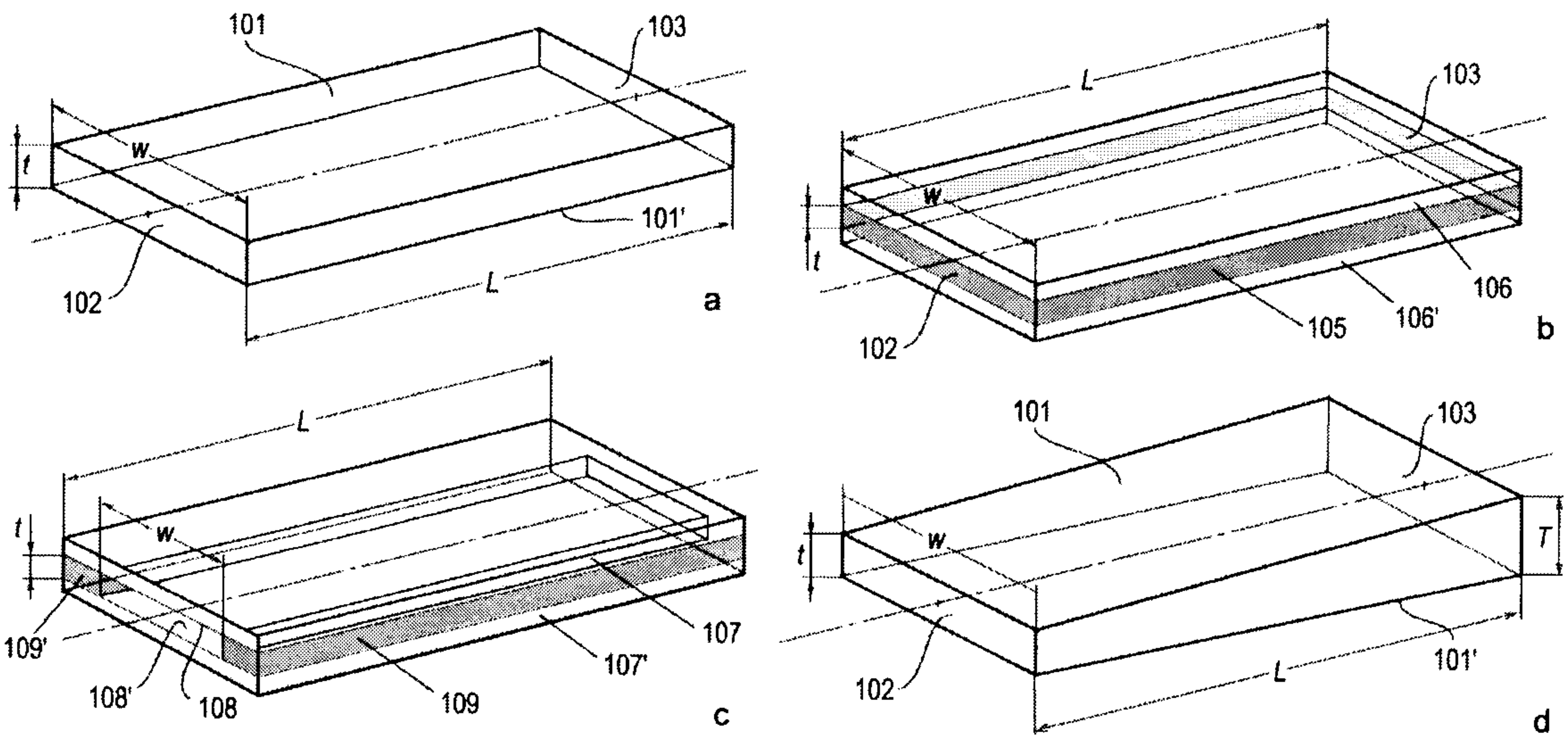
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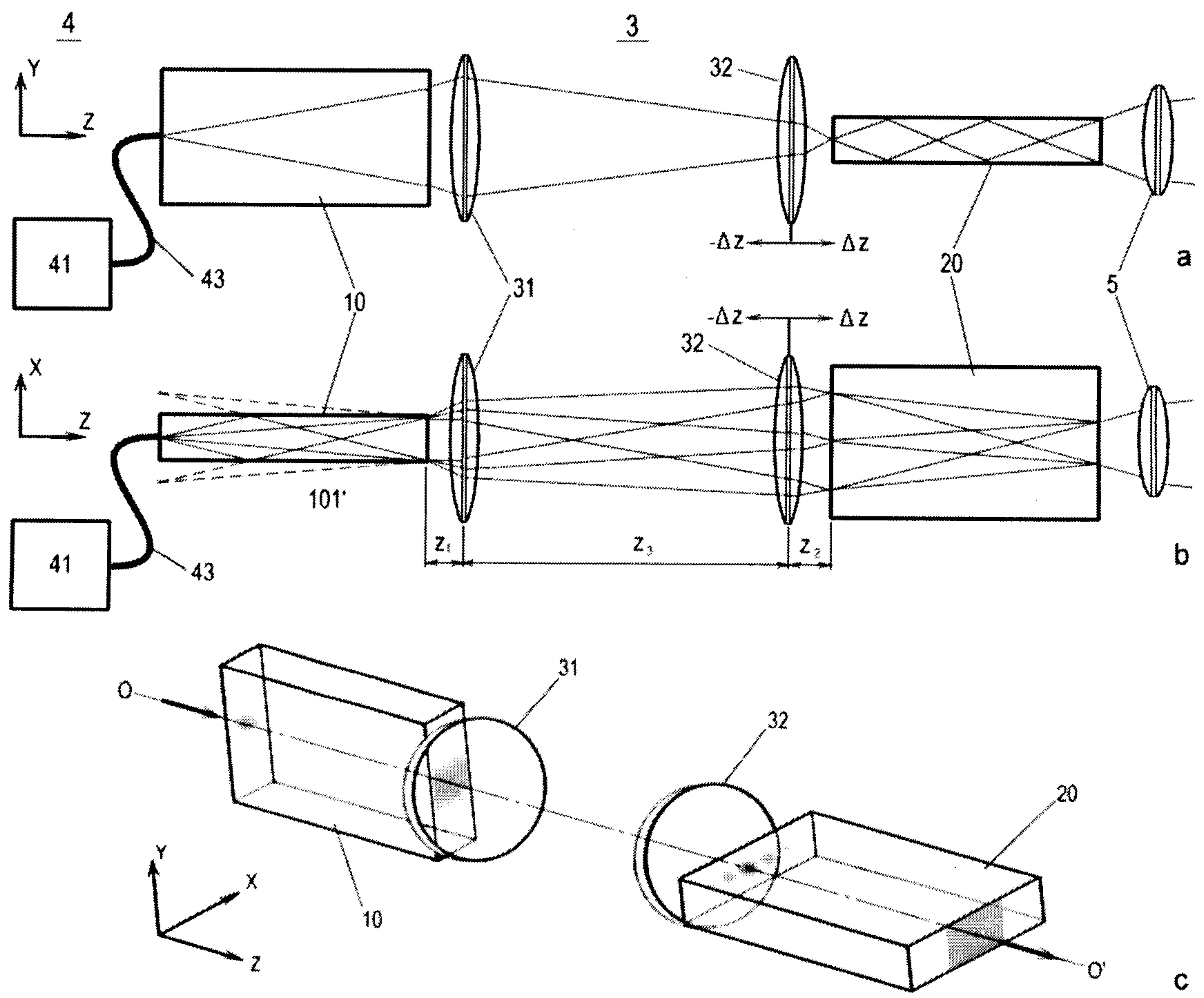
**FIG. 3**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O'
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**FIG. 4**

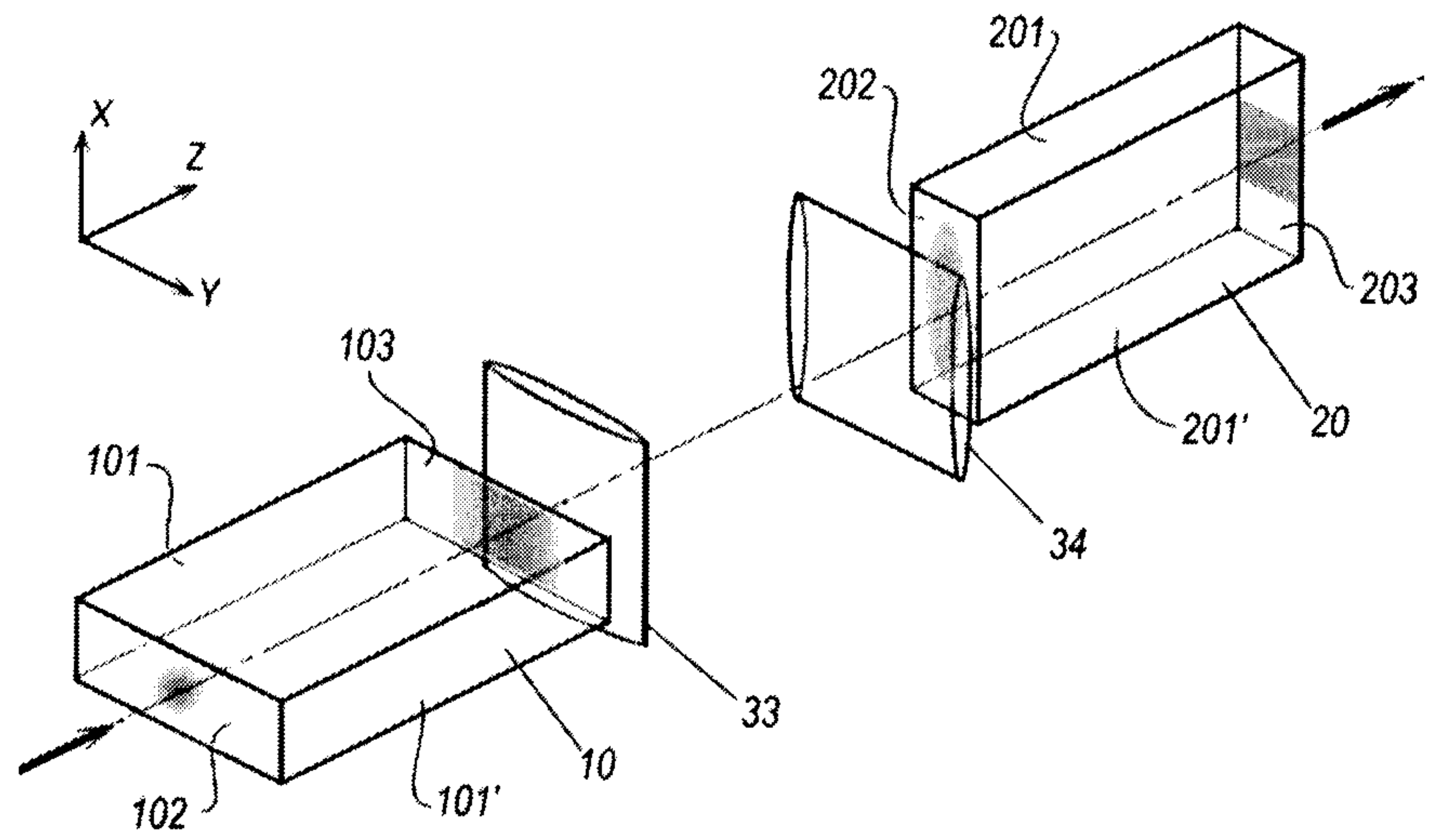


FIG. 5

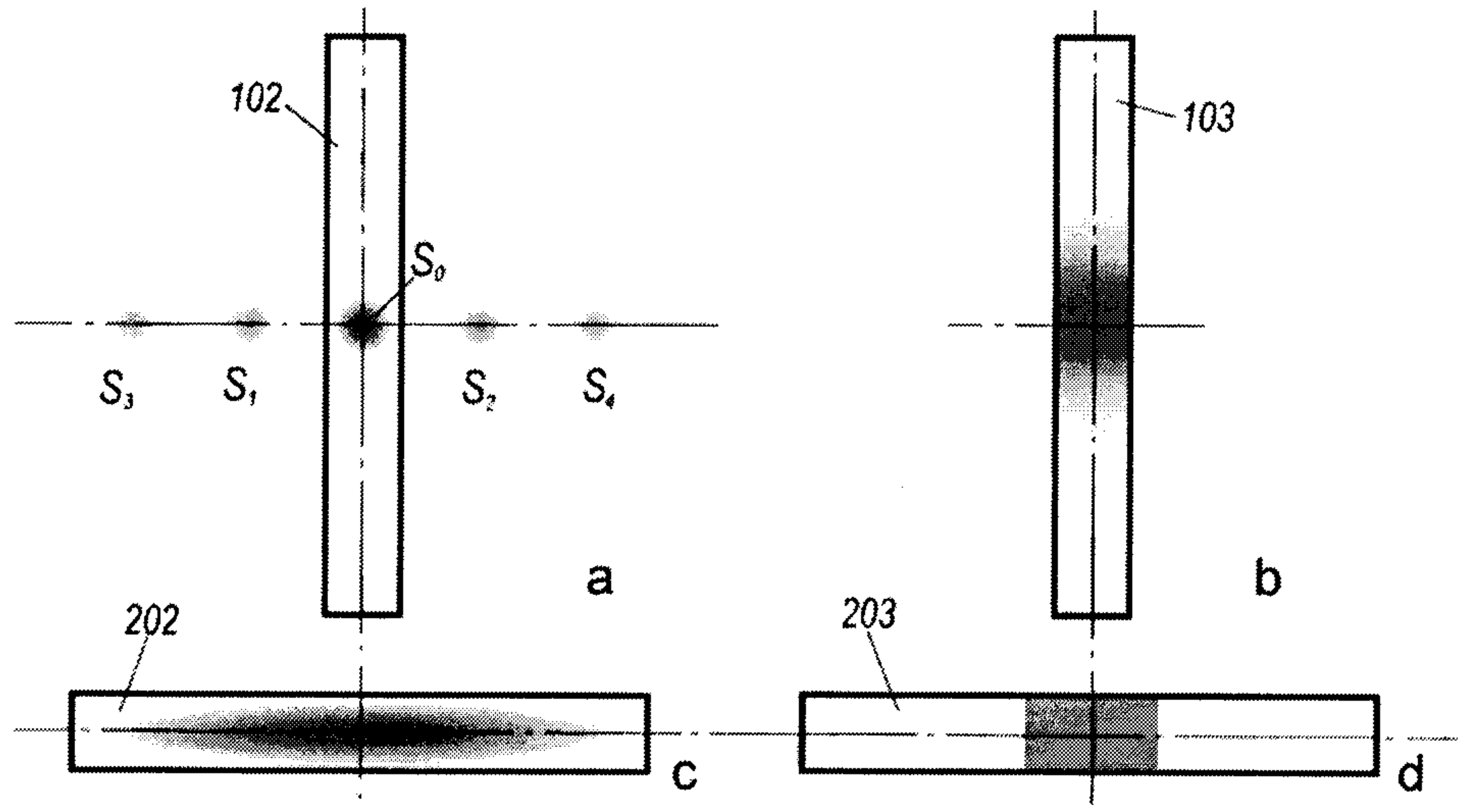


FIG. 6

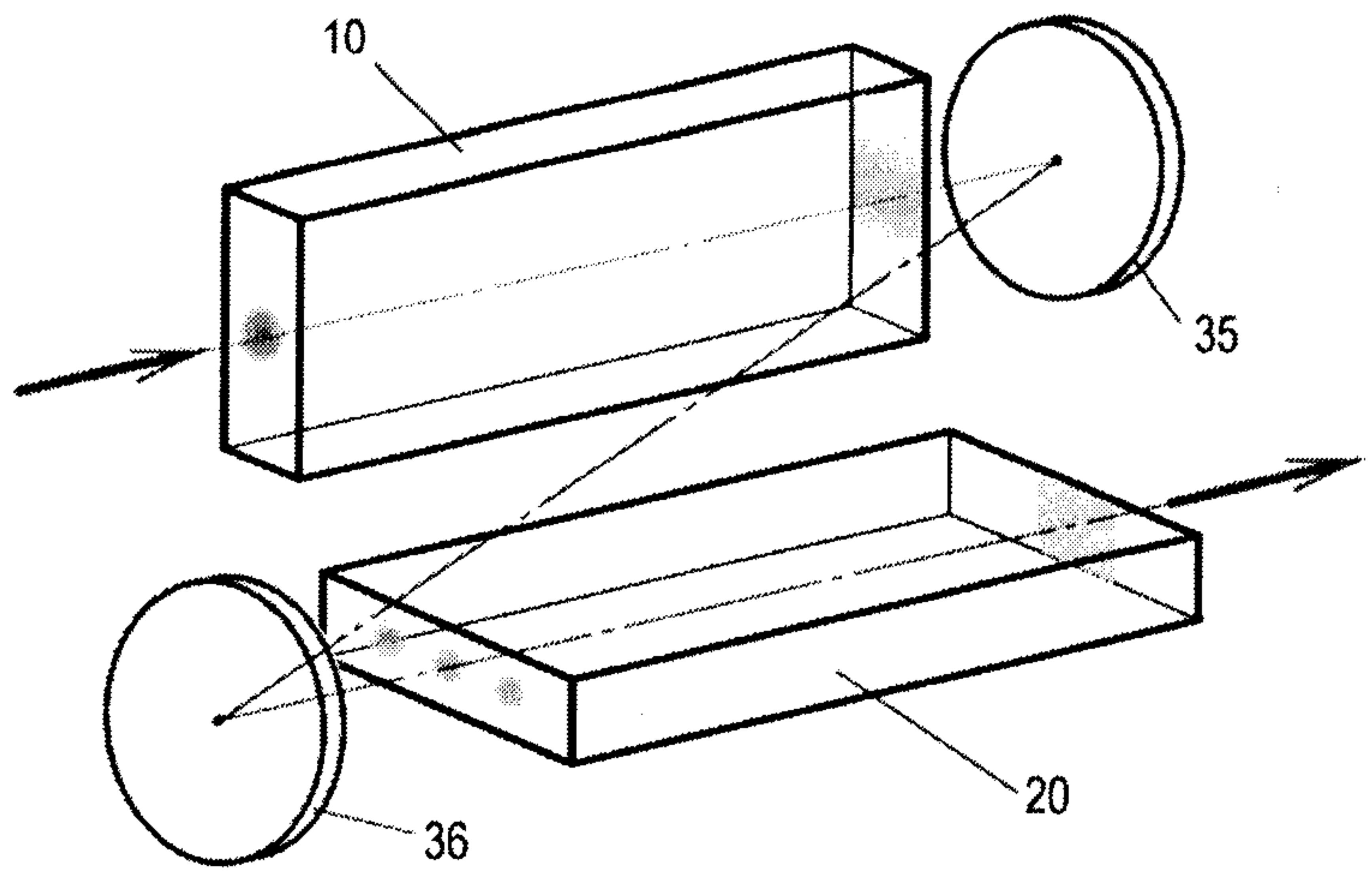


FIG. 7

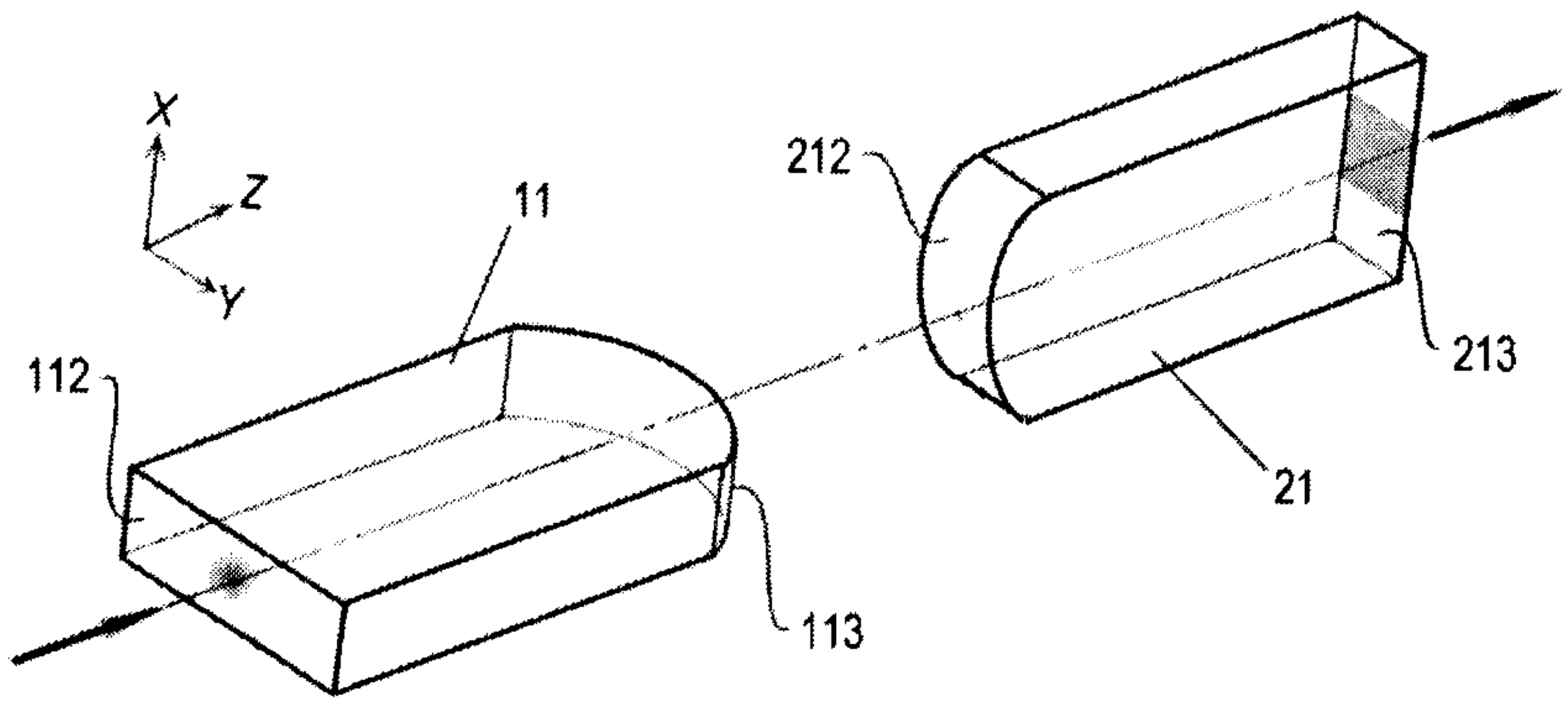


FIG. 8

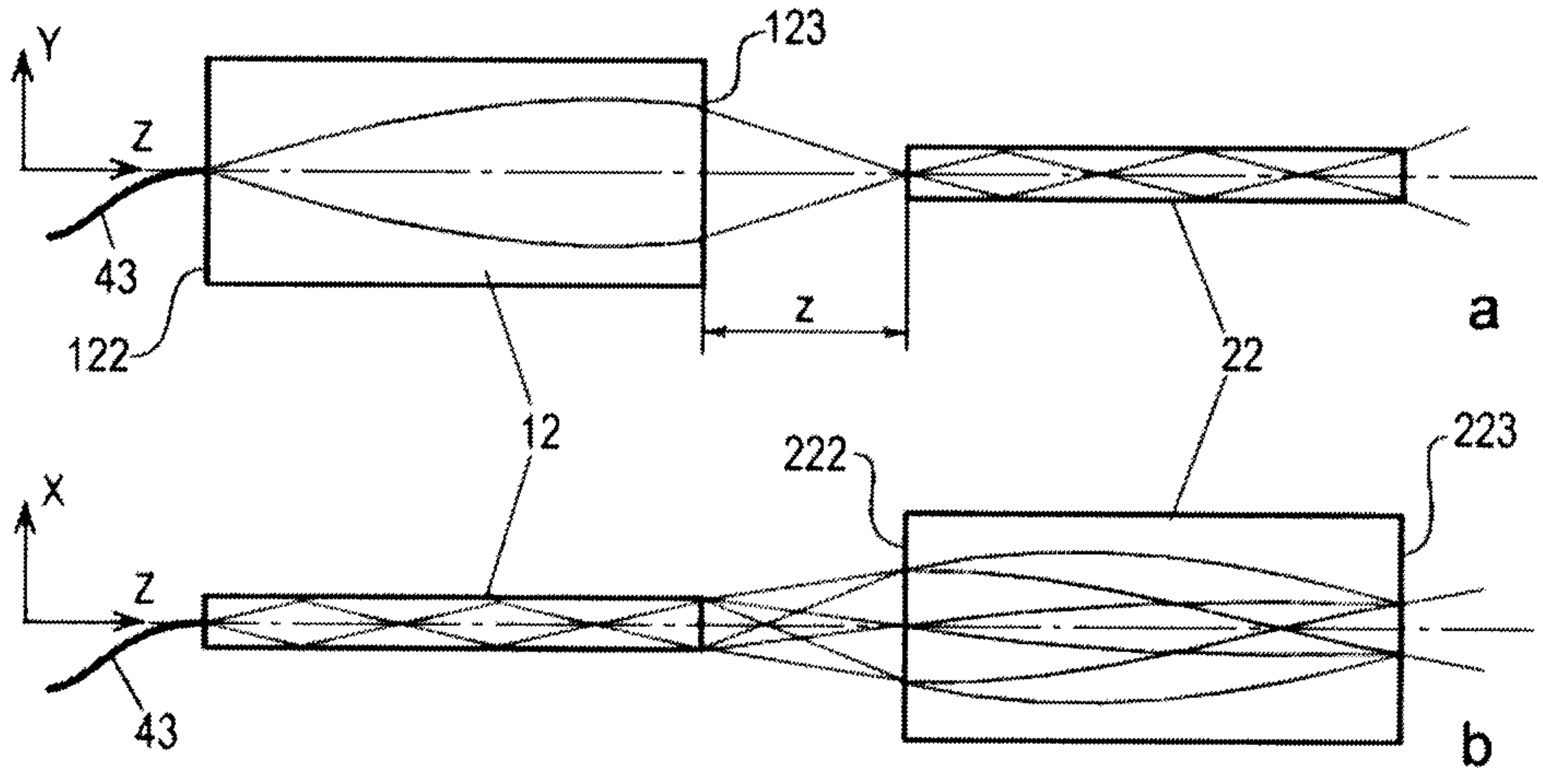


FIG. 9

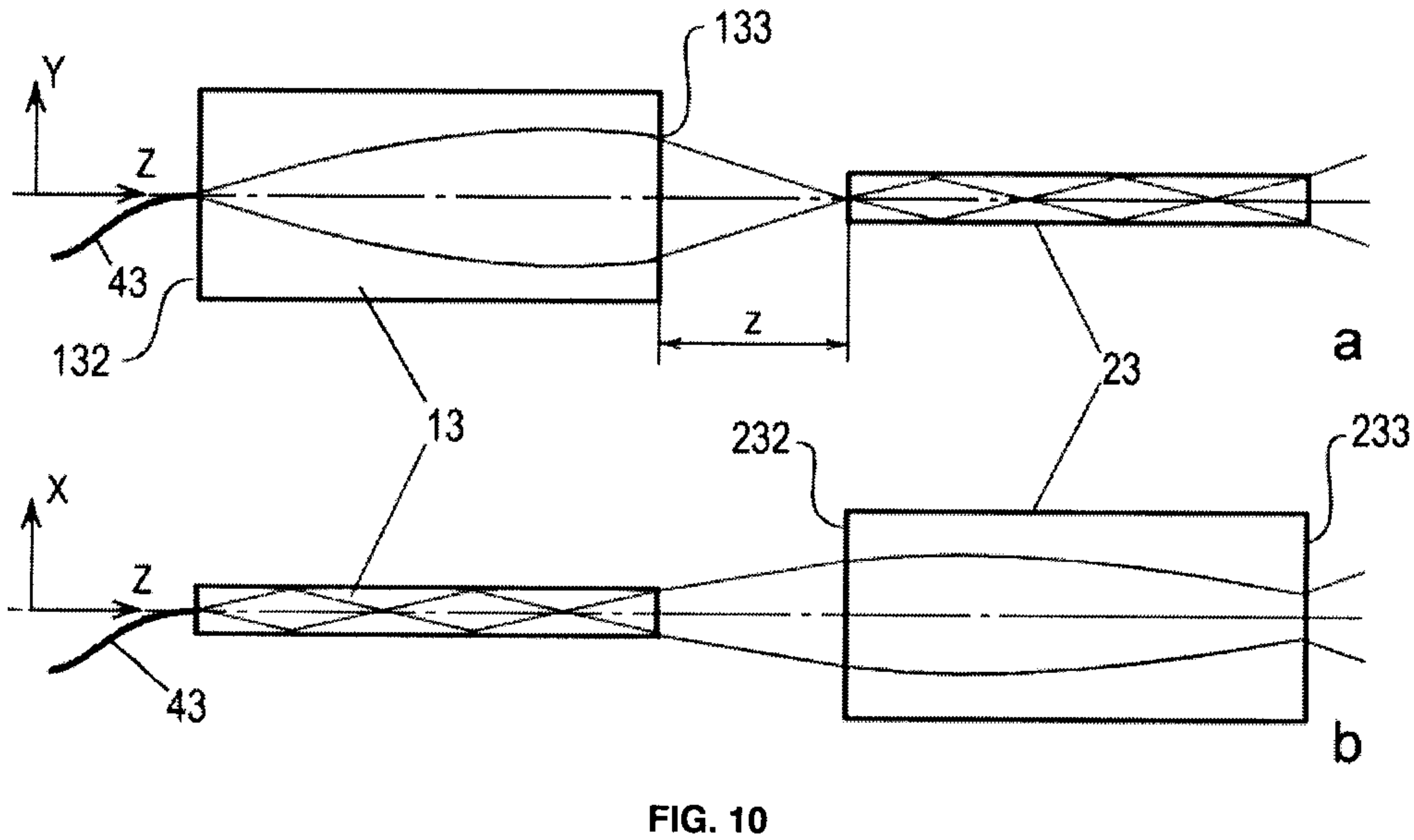


FIG. 10

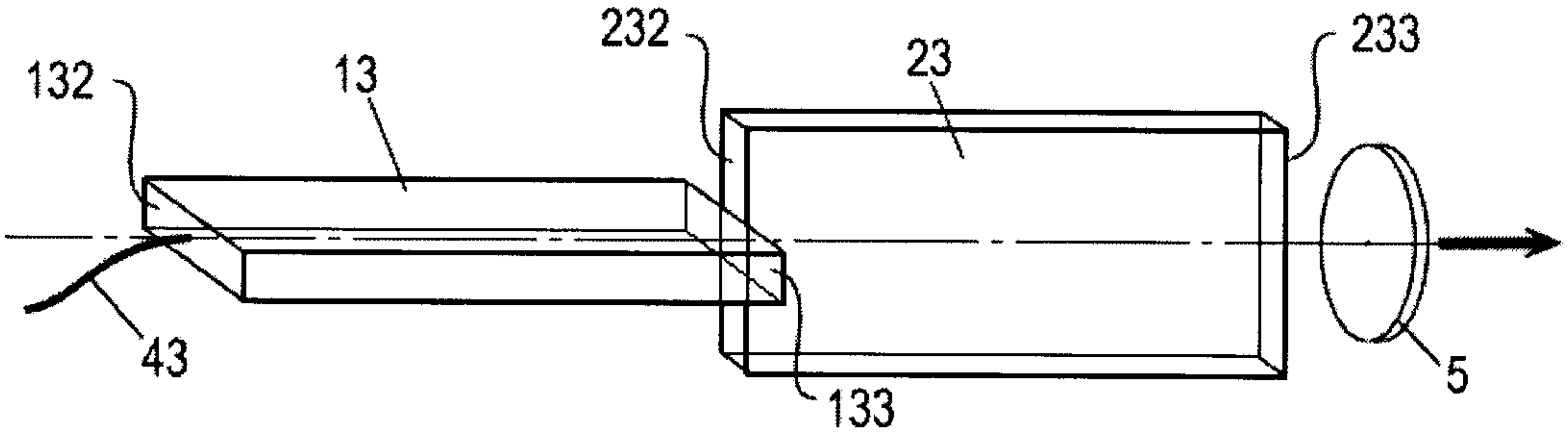


**FIG. 11**

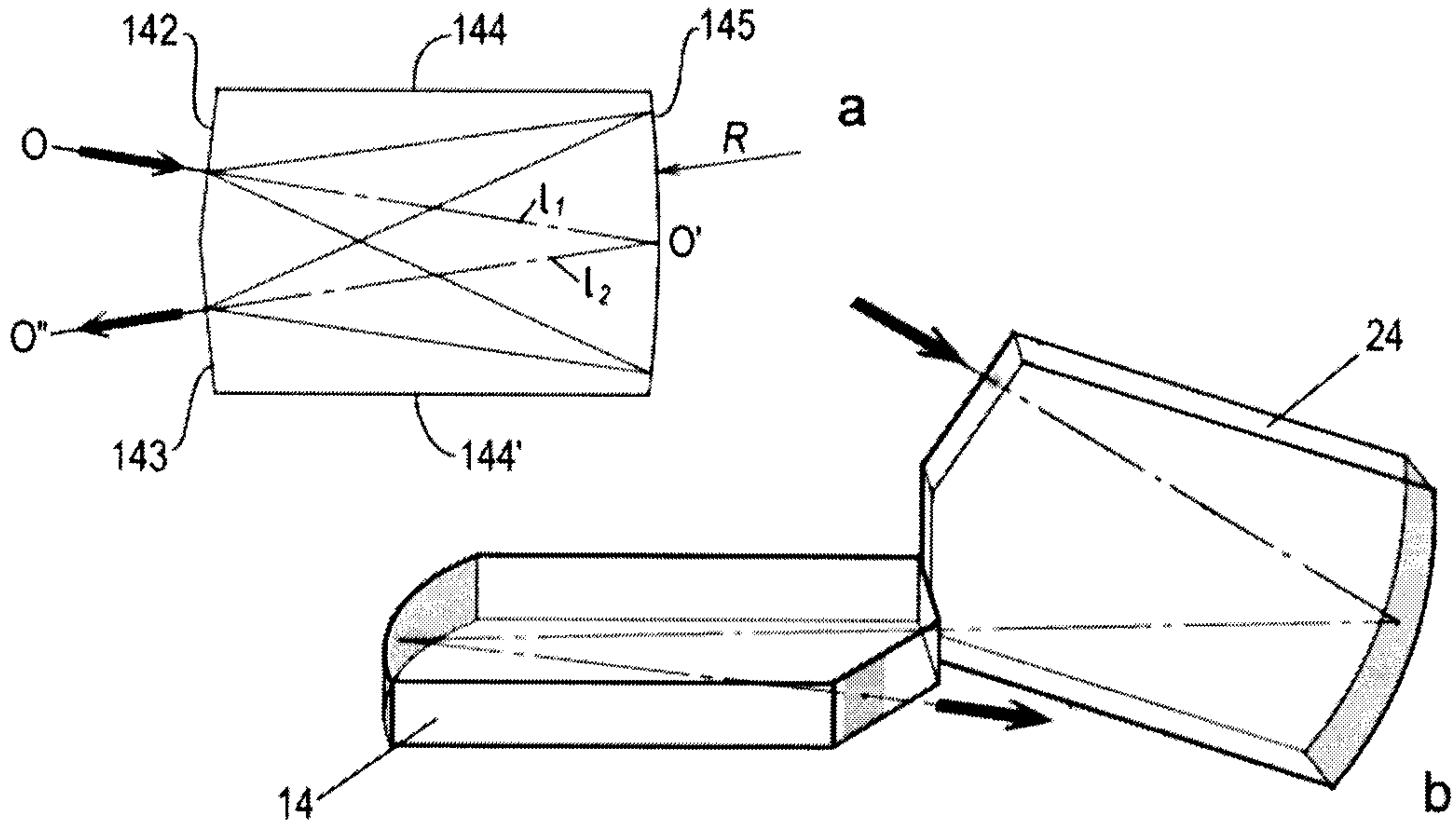


**FIG. 12**

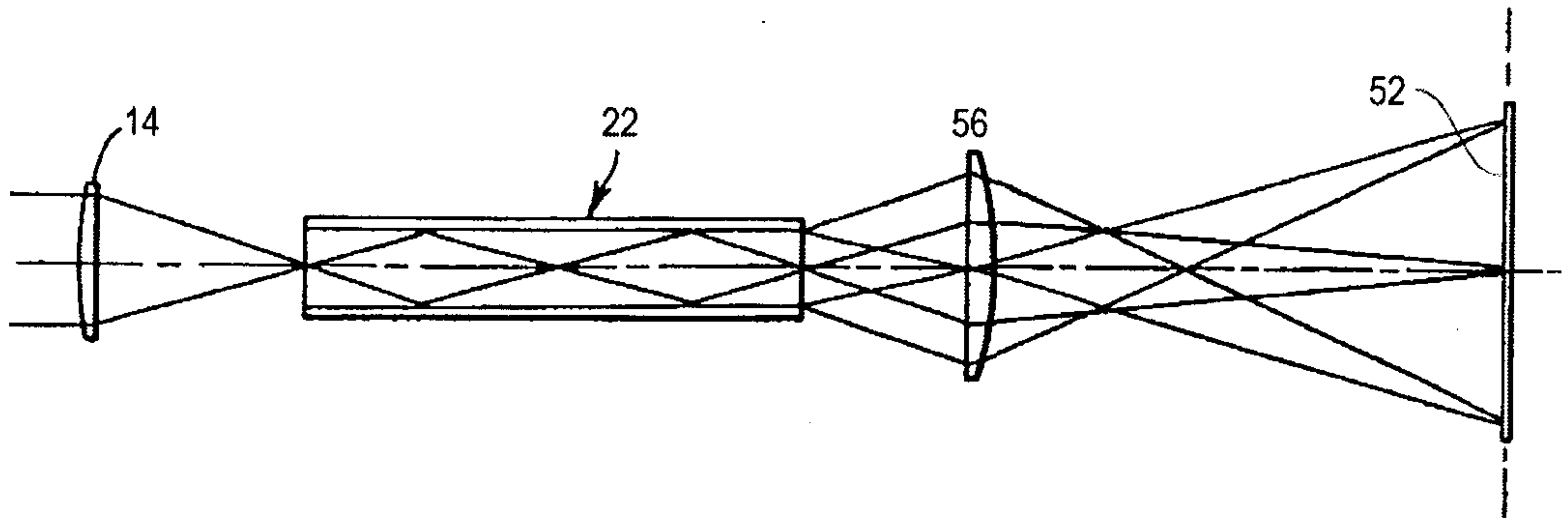


**FIG. 13, Prior Art**



CA 3017188 2018-09-12

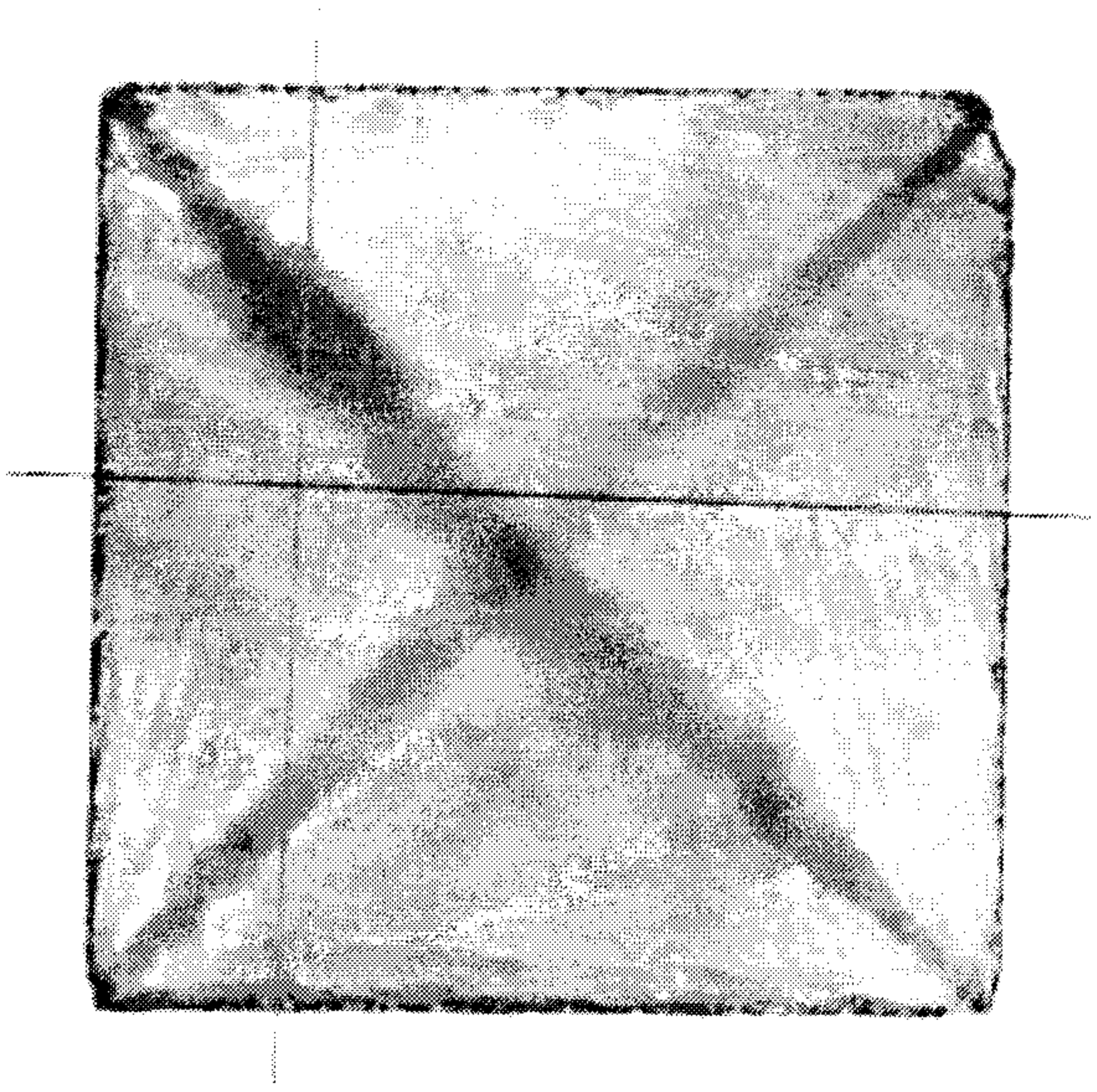

**FIG. 14, Prior Art**

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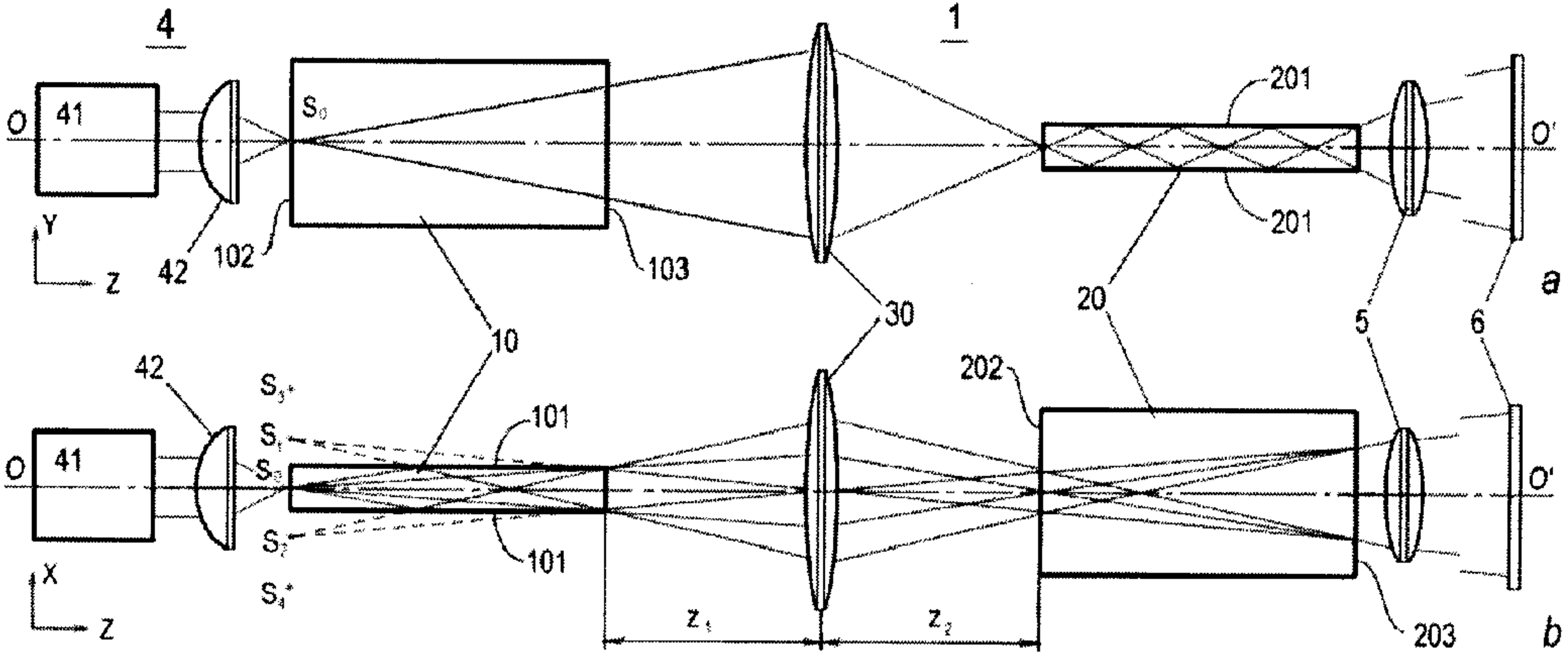
Date: September 12, 2018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