US012392999B2

(12) **United States Patent**
Shabtay et al.

(10) **Patent No.: US 12,392,999 B2**
(45) **Date of Patent: *Aug. 19, 2025**

(54) **FOLDED CAMERA LENS DESIGNS INCLUDING EIGHT LENSES OF +-+-+++-REFRACTIVE POWERS**

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(73) Assignee: **Corephotonics Ltd.**, Tel Aviv (IL)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **18/755,732**

(22) Filed: **Jun. 27, 2024**

(65) **Prior Publication Data**

US 2024/0345372 A1 Oct. 17, 2024

Related U.S. Application Data

(63) Continuation of application No. 17/607,400, filed as application No. PCT/IB2021/056357 on Jul. 14, 2021, now Pat. No. 12,050,308.

(60) Provisional application No. 63/054,862, filed on Jul. 22, 2020.

(51) **Int. Cl.**
G02B 13/00 (2006.01)
G02B 9/64 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 13/0065*** (2013.01); ***G02B 9/64*** (2013.01); ***G02B 13/0045*** (2013.01)

(58) **Field of Classification Search**
CPC ... G02B 13/0065; G02B 9/64; G02B 13/0045
See application file for complete search history.

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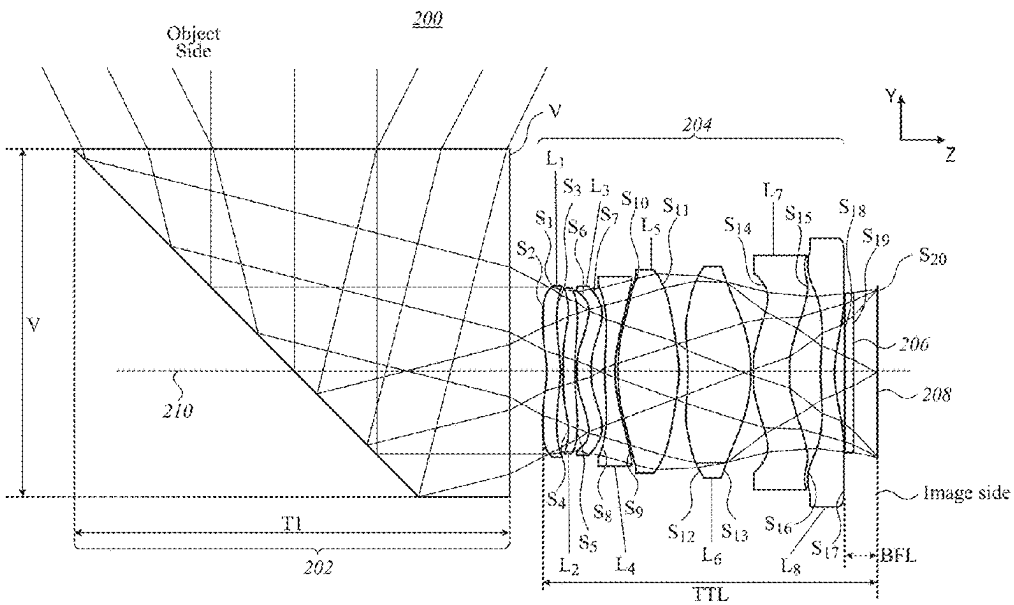
Primary Examiner — Wen Huang
(74) *Attorney, Agent, or Firm* — Nathan & Associates; Menachem Nathan

(57) **ABSTRACT**

Folded cameras with a total track length (TTL), f numbers smaller than 1.2 and large fields of view, e.g. of at least 60 degrees. Such folded cameras may comprise a lens with N≥7 lens elements, an image sensor and an optical path folding element for providing a folded optical path between an object and the lens, wherein an aperture stop of the lens is located closer to a first surface of the first lens element facing the object than a distance d that fulfills d/TTL=0.2.

18 Claims, 10 Drawing Sheets



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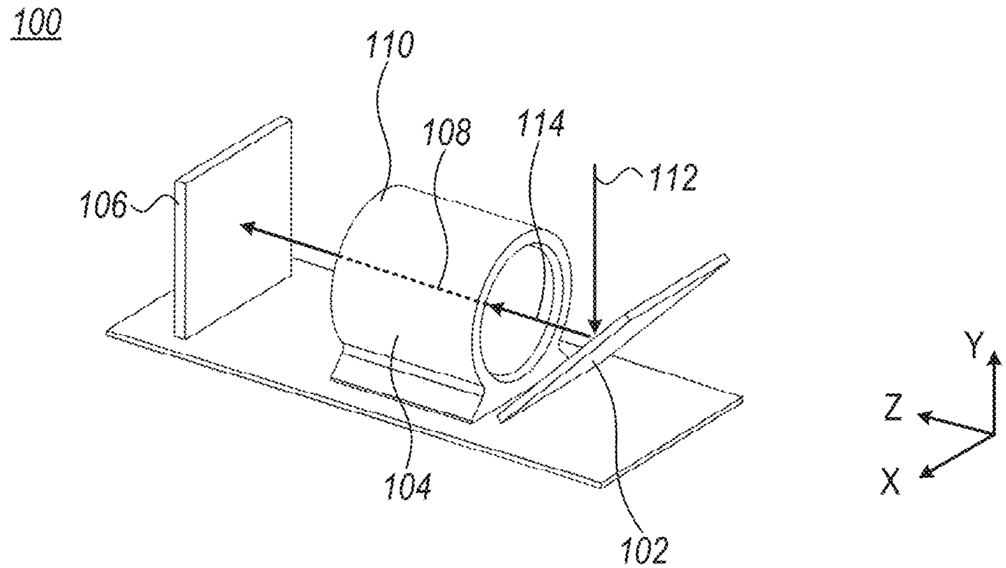

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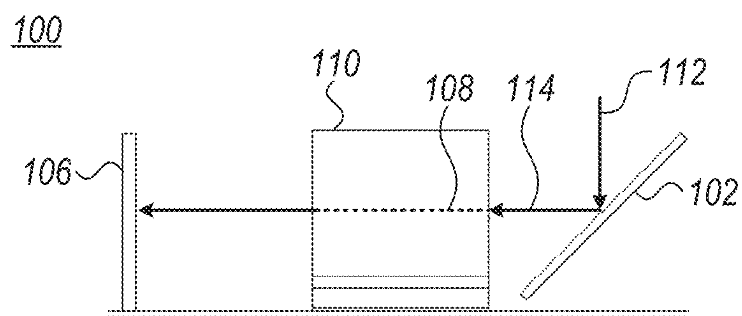

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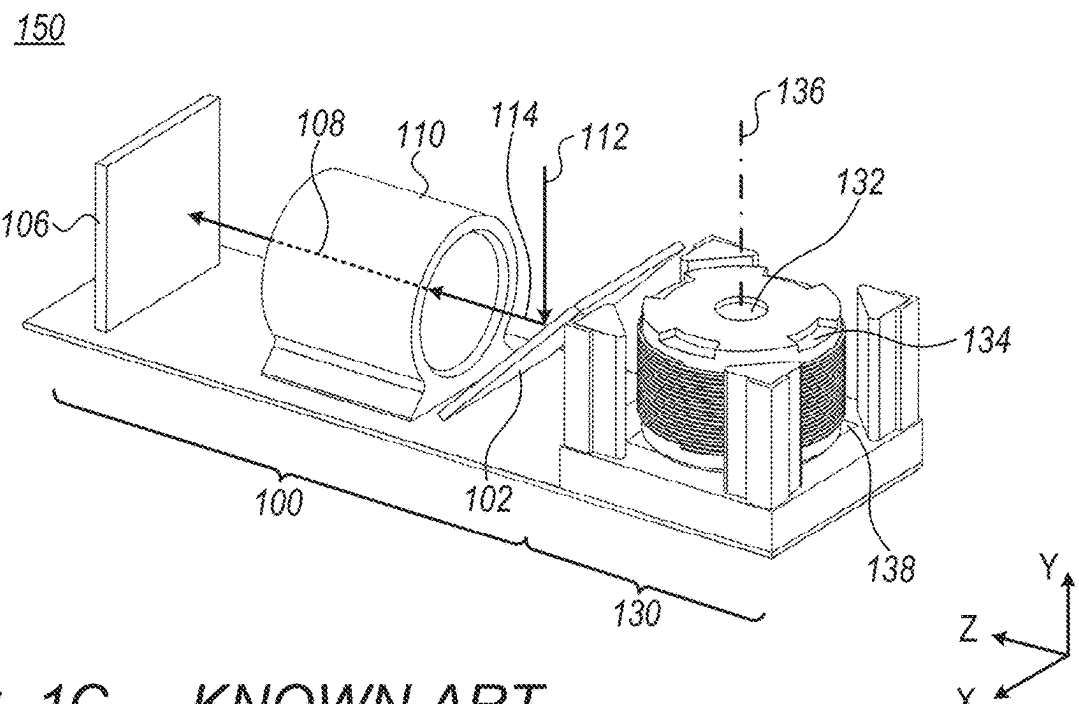

FIG. 1C KNOWN ART

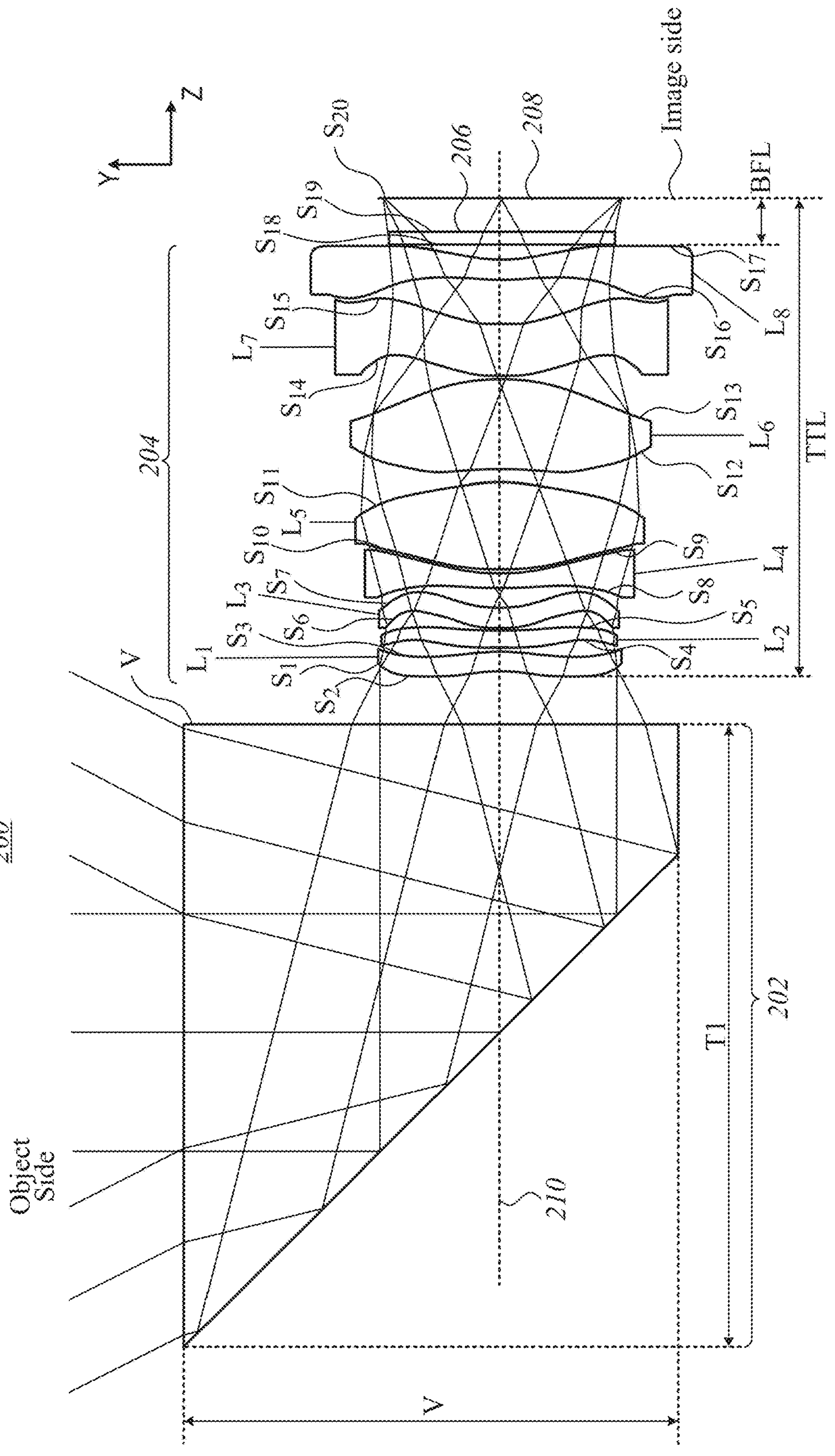
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FIG. 2A

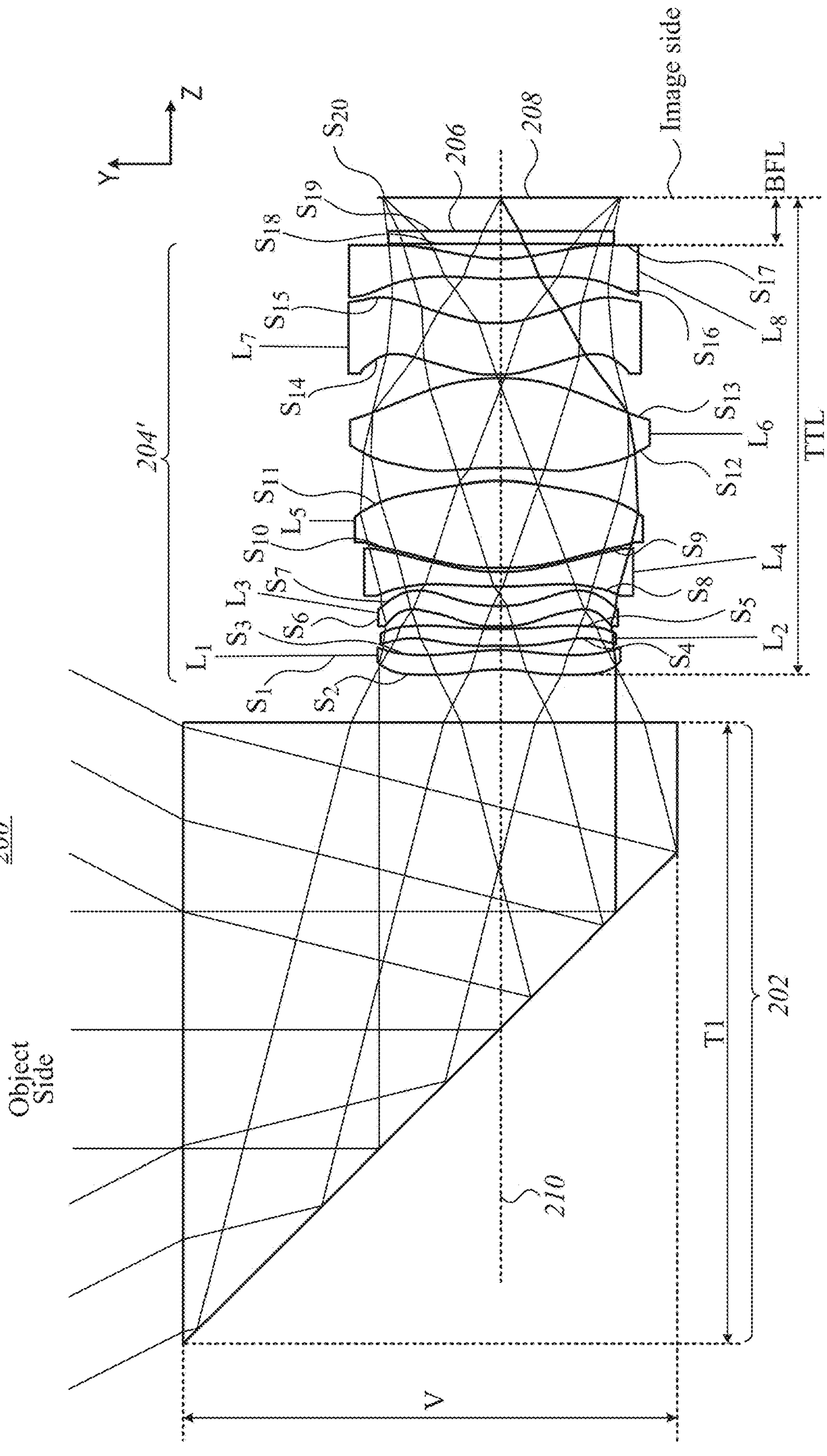

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FIG. 2B

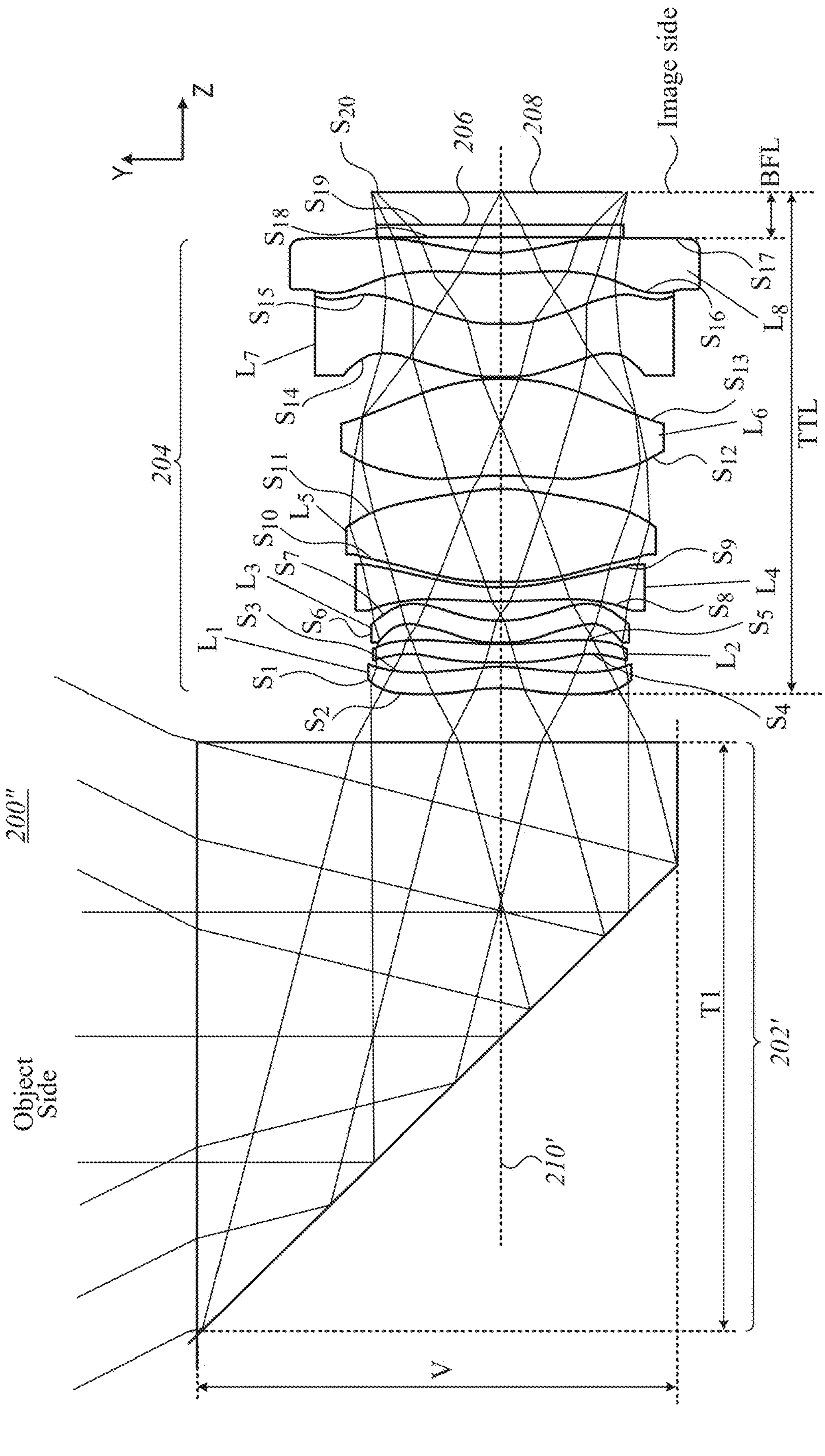
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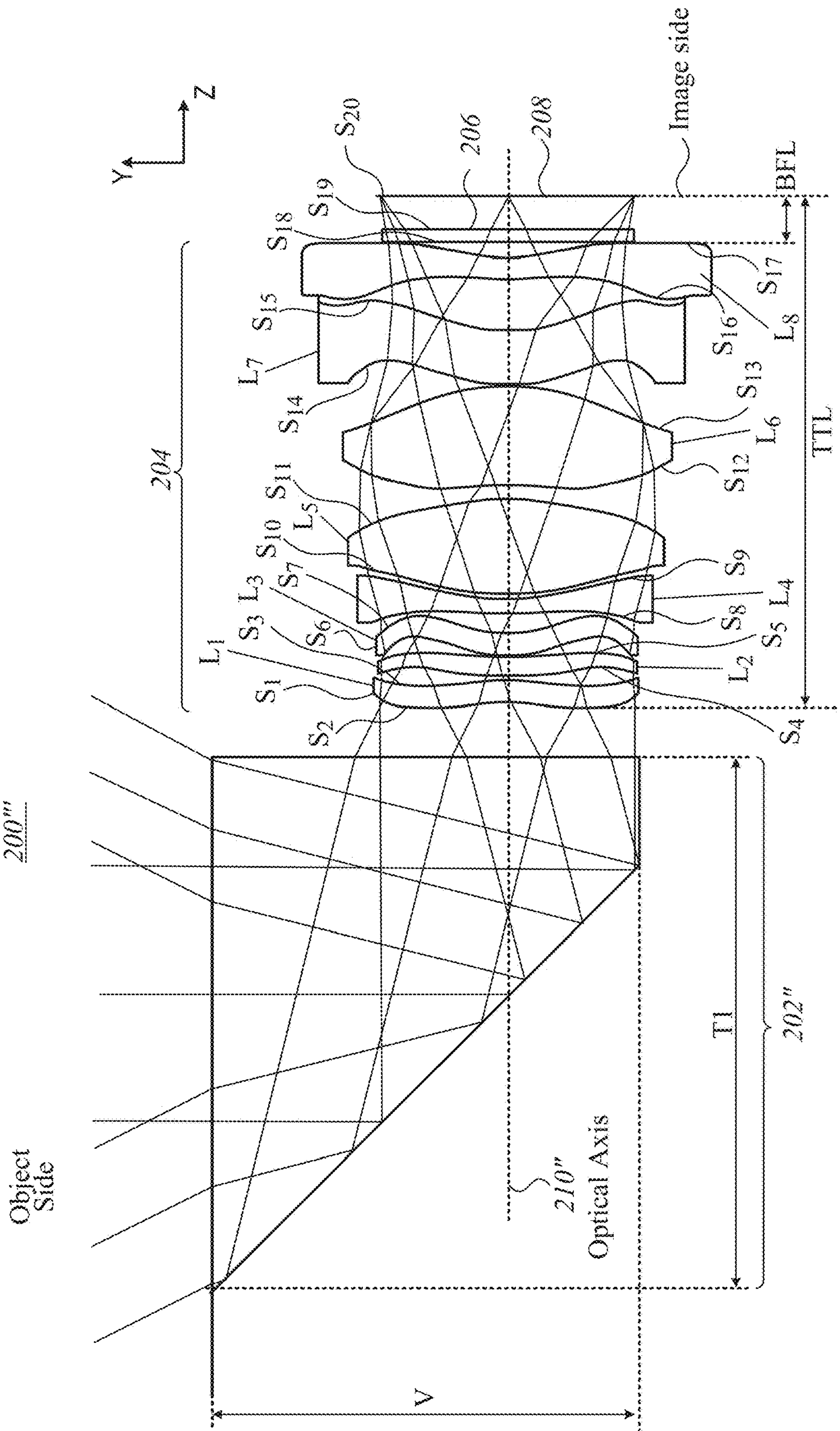
FIG. 2C



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200''
202''
204
206
208
210''
BFL
TTL
T1
V
L1
L2
L3
L4
L5
L6
L7
L8
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
S19
S20

FIG. 2D

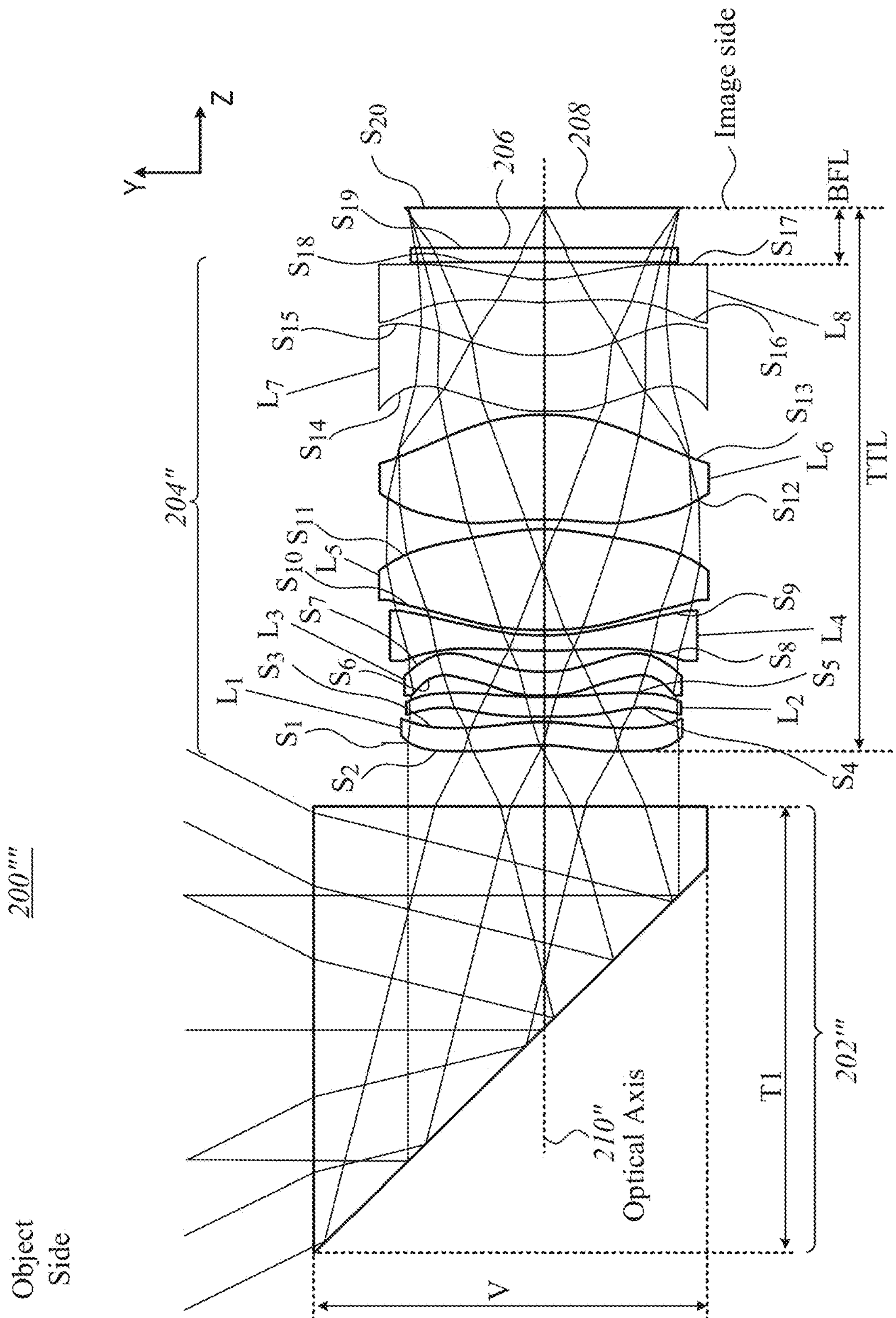
200''''
Object Side
Image side
Y
Z
204''
202''
206
208
210''
Optical Axis
T1
V
TTL
BFL
L_1
L_2
L_3
L_4
L_5
L_6
L_7
L_8
S_1
S_2
S_3
S_4
S_5
S_6
S_7
S_8
S_9
S_{10}
S_{11}
S_{12}
S_{13}
S_{14}
S_{15}
S_{16}
S_{17}
S_{18}
S_{19}
S_{20}

FIG. 2E

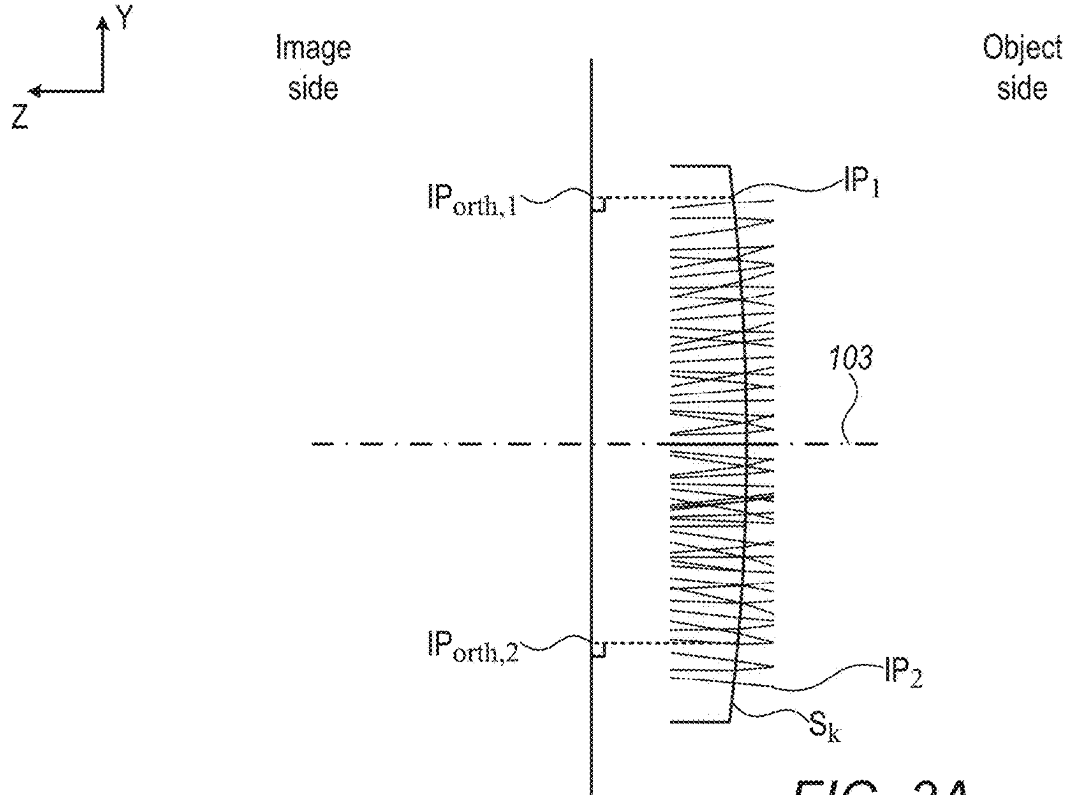
Y
Z
Image side
Object side
$IP_{orth,1}$
IP_1
103
$IP_{orth,2}$
IP_2
S_k

FIG. 3A

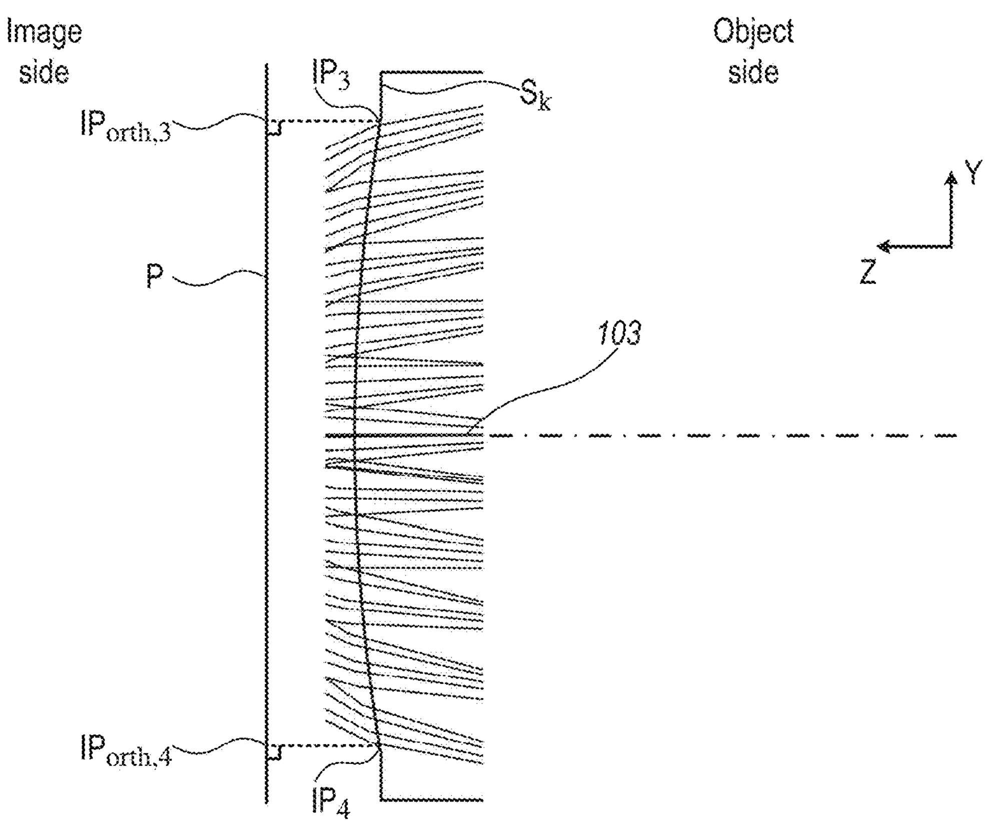
Image side
Object side
IP_3
S_k
$IP_{orth,3}$
Y
Z
P
103
$IP_{orth,4}$
IP_4

FIG. 3B

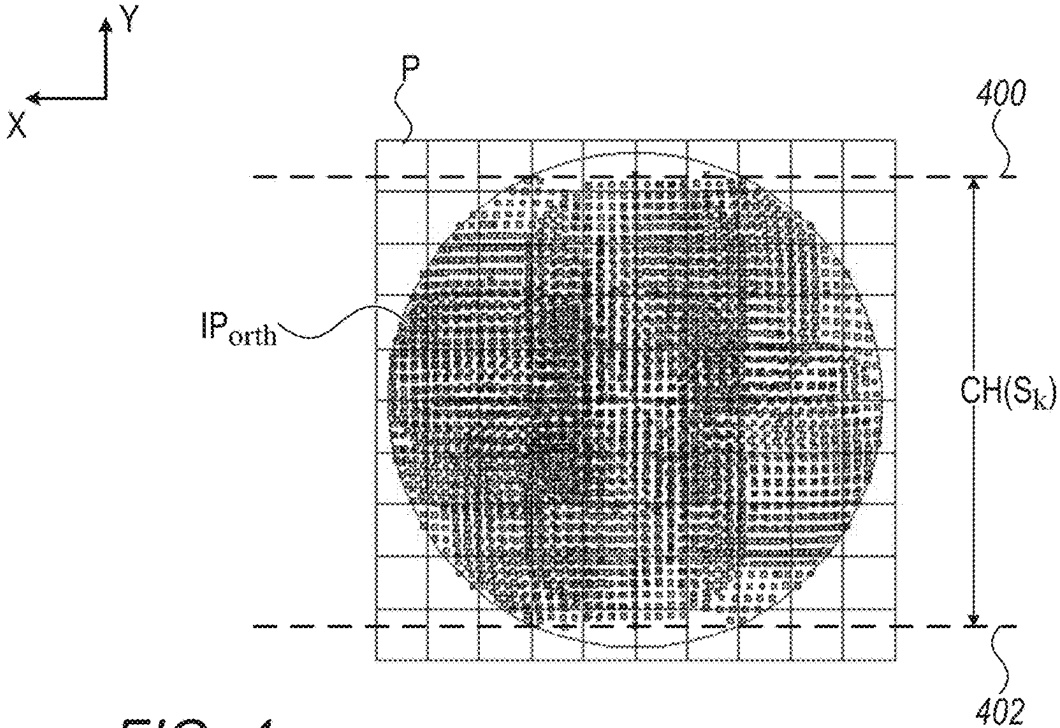

FIG. 4

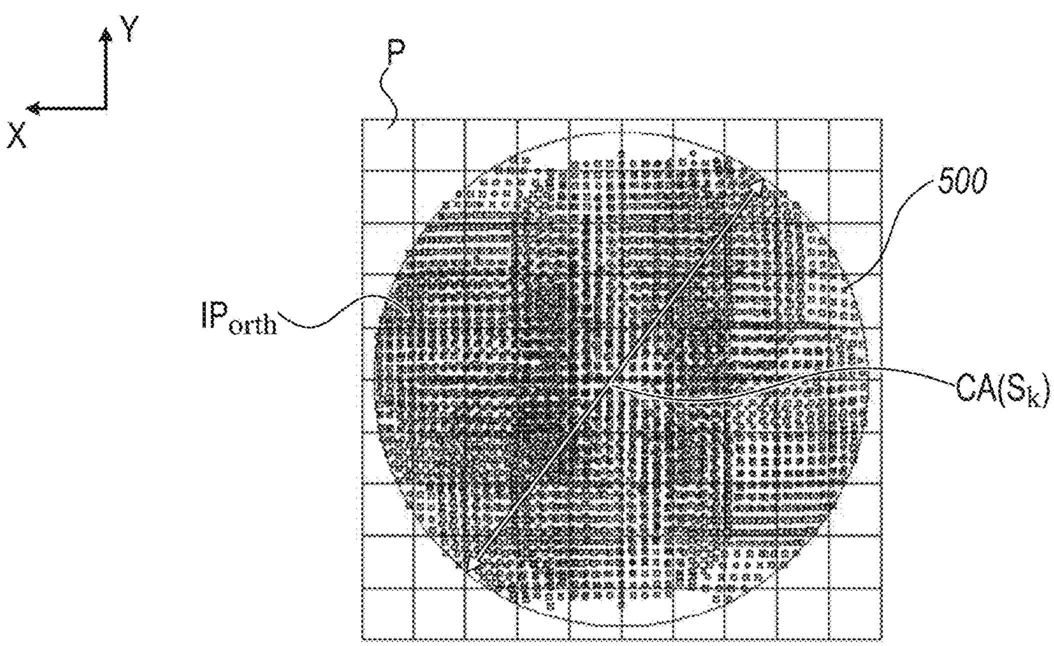

FIG. 5

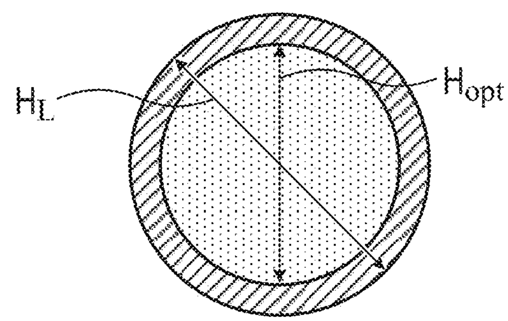

FIG. 6

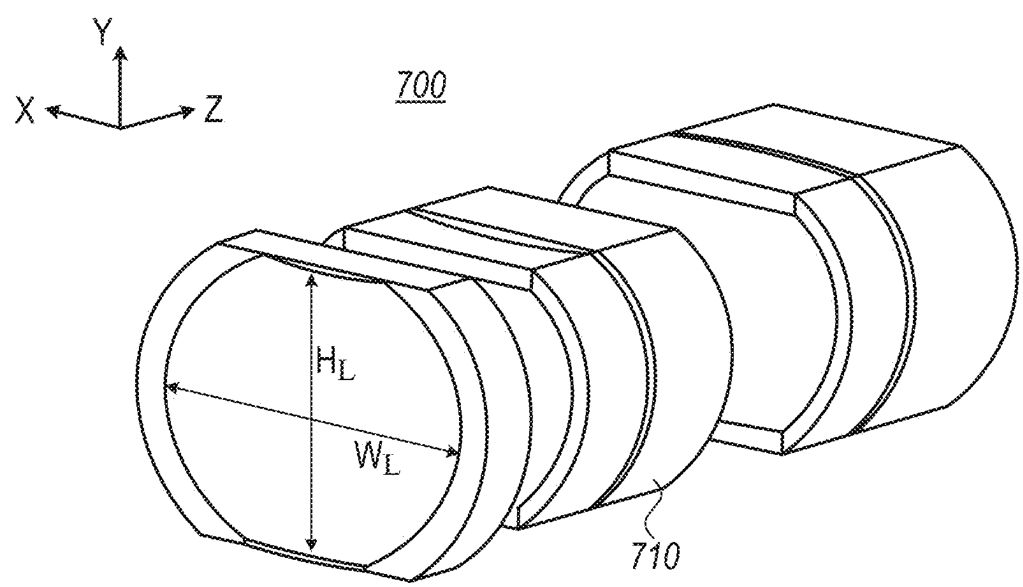

FIG. 7

FOLDED CAMERA LENS DESIGNS INCLUDING EIGHT LENSES OF +-+-+++-REFRACTIVE POWERS

CROSS REFERENCE TO EXISTING APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 17/607,400 filed Oct. 29, 2021 (now allowed), which was a 371 application from international patent application No. PCT/IB2021/056357 filed Jul. 14, 2021, and is related to and claims the benefit of U.S. Provisional patent application 63/054,862 filed Jul. 22, 2020, which is incorporated herein by reference in its entirety.

FIELD

The presently disclosed subject matter is related generally to the field of digital cameras and in particular to folded optical designs in such cameras.

Definitions

In this application and for optical and other properties mentioned throughout the description and figures, the following symbols and abbreviations are used, all of which are known in the art:

Total track length (TTL): the maximal distance, measured along a direction parallel to the optical axis, between a point of the front surface S_1 of a first lens element L_1 of a lens (or "lens assembly") and an image sensor, when a camera system including the lens is focused to an infinity object distance.

Back focal length (BFL): the minimal distance, measured along a direction parallel to the first optical axis, between a point of the rear surface S_{2N} of a last lens element L_N of a lens (or "lens assembly") and the image sensor, when a camera system including the lens is focused to an infinity object distance.

Effective focal length (EFL): the distance between a rear principal point P' and a rear focal point F' of a lens assembly of lens elements L_1 to L_N.

f-number, (f/#): the ratio of the EFL to an entrance pupil diameter.

BACKGROUND

Dual-cameras or triple-cameras (or multi-cameras in general) for mobile devices such as smartphones are known. In a typical triple-camera, one camera has an Ultra-Wide (UV) field of view (FOV) FOV_{UW}, another camera has a Wide field of view FOV_W narrower than FOV_{UW} and yet another camera has Tele field of view FOV_T narrower than FOV_W. These cameras are also referred to herein as, respectively, an Ultra-Wide (or UW) camera, a Wide (or W) camera and a Tele (or T) camera. In general, the Wide camera is considered to be a smartphone's main camera.

The f-number ("f/#") of a camera lens is the ratio of the effective focal length (EFL) to the diameter D of the camera's entrance pupil: f/#=EFL/D. The entrance pupil is the optical image of the aperture stop, as 'seen' through the front aperture of the lens system. The front aperture is the object-sided aperture of the lens. A low f/# is desired for a smartphone's main camera as it has 3 major advantages: good low light sensitivity, strong "natural" Bokeh effect and high image resolution, discussed next:

1. Low light sensitivity is a major performance drawback of today's mobile device compatible cameras when compared to e.g. digital single-lens reflex (DSLR) cameras. As an example, halving a camera's f/#(for same EFL) increases the aperture area by a factor of 4, meaning that 4 times more light enters the camera. This difference is especially relevant when capturing low light scenes.

2. Bokeh is the aesthetic quality of the blur produced in the out-of-focus segments of an image, and it is a highly demanded feature for today's smartphones. The Bokeh effect correlates inversely with the depth of field (DOF) of an image, wherein DOF~f/#. A low f/# is beneficial for supporting strong "natural" Bokeh effects. As the f/#s present in today's smartphone cameras do not provide sufficient "natural" Bokeh, the demand for strong Bokeh is answered by "artificial" Bokeh, i.e. artificially applying blur to out-of-focus image segments.

3. Image sensors with continuously increasing pixel resolution are entering mobile devices, exceeding 100 megapixel in 2019 for the first time. This (amongst other factors) is achieved by shrinking the size of single pixels, i.e. increasing the spatial pixel frequency. For translating pixel resolution to image resolution, a camera's lens must support the spatial pixel frequency k_{Pixel} of the sensor. For a well-designed (diffraction-limited) camera lens, the resolvable spatial frequency of the lens k_{Lens} depends inversely on the f/#: k_{Lens}~1/f/#, i.e. a lower f/# corresponds to a higher image resolution (assuming an image sensor with sufficient spatial pixel frequency).

The latest premium smartphones are equipped with main Wide cameras that have f/# of about f/1.9 (Huawei P40 Pro) and f/1.8 (Apple iphone 11 Pro Max). A major challenge in low f/# cameras is the design of lenses that correct for the strong aberration imposed by the large front apertures required, e.g. for correction of chromatic aberration. This is usually tackled by a more complex lens design that includes a larger number of lens elements. However, this generally leads to larger total track length (TTL) and larger camera module heights, what is detrimental to the goal of slim smartphone design.

A recent development in mobile Tele cameras involves using a prism to "fold" the Tele camera: a reflecting or optical path folding element ("OPFE") is added to the optical path in order to "fold" (tilt) the light propagation direction from perpendicular to the back surface of a host device to parallel to the host device's back surface. Folded cameras allow large TTLs in a slim camera design.

For improving a smartphone's main camera it would be beneficial to have a folded Wide camera designs with low f/#.

SUMMARY

In various embodiments there are provided folded cameras, comprising: a lens with N 7 lens elements L_i, having an effective focal length (EFL), each L_i having a respective focal length f_i wherein a first lens element L_1 faces an object side; an image sensor; and an OPFE for providing a folded optical path between an object and the lens, to the lens optical axis, wherein a folded camera has a total track length (TTL), wherein an aperture stop of the lens is located closer to a first surface of the first lens element facing the object than a distance d that fulfills d/TTL=0.2, and wherein an f number f/# of the camera is smaller than 1.2.

In various embodiments there are provided folded cameras, comprising: a lens having an effective focal length (EFL) and including N≥7 lens elements L_i having a first optical axis, each lens element having a respective focal length f_i and comprising a respective front surface S_{2i-1} and a respective rear surface S_{2i}, the lens element surfaces marked S_k where $1 \le k \le 2N$, wherein each lens element surface S_k has a clear height value $CH(S_k)$, wherein clear height value $CH(S_{17})$ of surface S_{17} is greater than or equal to a clear height value of each of surfaces S_2 to S_{2N-1}; an image sensor; and an OPFE for providing a folded optical path between an object and the lens elements, and wherein an f number f/# of the camera is smaller than 1.2.

In some embodiments, f/#<1.1.

In some embodiments, f/#≤1.0.

In some embodiments, 0.8<f/#≤1.0.

In some embodiments, a folded camera as above or below has a diagonal FOV that is larger than 60 degrees.

In some embodiments, $|f_i| > 4 \cdot EFL$ for $1 \le i \le 3$.

In some embodiments, $|f_i| > 5 \cdot EFL$ for $1 \le i \le 3$.

In some embodiments, L_5 is the lens element with the strongest optical power, i.e. $|f_5| < |f_i|$ for $i \ne 5$.

In some embodiments, $f_5 < EFL$.

In some embodiments, a lens sub-system including lens elements L_4 and L_5 has positive refractive power.

In some embodiments, focal lengths f_4 of L_4 and f_5 of L_5 satisfy $|f_4| < 4 \cdot f_5$.

In some embodiments, focal lengths f_4 of L_4 and f_5 of L_5 satisfy $|f_4| < 3 \cdot f_5$.

In some embodiments, the lens includes at least one air gap between lens elements that comply with the condition STD<0.020, where STD is a normalized gap standard deviation.

In some embodiments, the lens includes at least one air gap between lens elements that comply with the condition STD<0.010, where STD is a normalized gap standard deviation.

In some embodiments, an air gap between lens elements L_4 and L_5 satisfies STD<0.020, where STD is a normalized gap standard deviation.

BRIEF DESCRIPTION OF THE DRAWINGS

Non-limiting examples of embodiments disclosed herein are described below with reference to figures attached hereto that are listed following this paragraph. The drawings and descriptions are meant to illuminate and clarify embodiments disclosed herein, and should not be considered limiting in any way. Like elements in different drawings may be indicated by like numerals. Elements in the drawings are not necessarily drawn to scale. In the drawings:

FIG. **1**A illustrates a known digital folded camera that may operate as a Wide camera in a perspective view;

FIG. **1**B shows the camera of FIG. **1**A in a side view;

FIG. **1**C illustrates a known dual camera that includes a folded camera as in FIGS. **1**A and **1**B together with an "upright" (non-folded) camera;

FIG. **2**A shows a schematic view of a folded optical lens system according to some examples of the presently disclosed subject matter;

FIG. **2**B shows a schematic view of another folded optical lens system according to some examples of the presently disclosed subject matter;

FIG. **2**C shows a schematic view of yet another folded optical lens system according to some examples of the presently disclosed subject matter;

FIG. **2**D shows a schematic view of yet another folded optical lens system according to some examples of the presently disclosed subject matter;

FIG. **2**E depicts schematically yet another folded optical lens system disclosed herein;

FIG. **3**A illustrates the orthogonal projections $IP_{orth,1}$, $IP_{orth,2}$ of two impact points IP_1 and IP_2 on a plane P that is orthogonal to the optical axis of the lens of the system in FIGS. **2**A-**2**D;

FIG. **3**B illustrates the orthogonal projections $IP_{orth,3}$, $IP_{orth,4}$ of two impact points IP_3 and IP_4 on a plane P that is orthogonal to the optical axis of the lens of the system in FIGS. **2**A-**2**D;

FIG. **4** provides graphically a definition of clear height;

FIG. **5** provides graphically a definition of clear aperture;

FIG. **6** provides a graphical illustration of diameter H_{Li} of lens element L_i;

FIG. **7** shows an exploded view of lens elements illustrating lens element width W_{Li} and height H_{Li}.

DETAILED DESCRIPTION

In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding. However, it will be understood by those skilled in the art that the presently disclosed subject matter may be practiced without these specific details. In other instances, well-known methods have not been described in detail so as not to obscure the presently disclosed subject matter.

It is appreciated that certain features of the presently disclosed subject matter, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the presently disclosed subject matter, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable sub-combination.

Furthermore, for the sake of clarity the term "substantially" is used herein to imply the possibility of variations in values within an acceptable range. According to one example, the term "substantially" used herein should be interpreted to imply possible variation of up to 10% over or under any specified value. According to another example, the term "substantially" used herein should be interpreted to imply possible variation of up to 5% over or under any specified value. According to a further example, the term "substantially" used herein should be interpreted to imply possible variation of up to 2.5% over or under any specified value.

FIGS. **1**A and **1**B illustrate a known digital folded camera **100**, which may operate for example as a Wide camera. Camera **100** comprises an optical path folding element (OPFE) **102** e.g. a prism, a lens **104** with a plurality of lens elements (not visible in this representation, but visible e.g. in FIGS. **2**A-D) and an image sensor **106**. In some embodiments (as in FIGS. **2**A-**2**D), the lens elements are axial symmetric along a first optical axis **108**. In other embodiments the lens elements may not be axial symmetric. For example, lens elements may be cut (or diced or sliced) to a non-circular shape, as e.g. demonstrated in FIG. **2**B.

At least some of the lens elements can be held by a structure called a "barrel" **110**. The barrel may have a longitudinal symmetry along optical axis **108**. In FIGS. **1**A to **1**C, the cross-section of this barrel is circular. This is however not mandatory and other shapes can be used, e.g. for hosting cut lens elements.

The path of the optical rays from an object (not shown) to image sensor **106** defines an optical path (see optical paths **112** and **114**, which represent portions of the optical path).

OPFE folds the optical path from a first optical path **112** to a second optical path **114**. Optical path **114** is substantially parallel to the optical axis **108**. The optical path is thus referred to as "folded optical path" (indicated by optical paths **112** and **114**) and camera **100** is referred to as "folded camera".

In particular, in some examples, OPFE **102** is inclined at substantially 45° with respect to optical axis **108**. In FIG. **1**A, OPFE **102** is also inclined at substantially 45° with respect to optical path **112**.

In some known examples, image sensor **106** lies in a X-Y plane substantially perpendicular to optical axis **108**. This is however not limiting and the image sensor **106** can have a different orientation. For example, and as described in WO 2016/024192, image sensor **106** can be in the XZ plane. In this case, an additional OPFE can be used to reflect the optical rays towards image sensor **106**.

Two cameras, for example a Wide camera **100** and a regular UW camera **130** may be included in a digital camera **150** (also referred to as dual-camera). A possible configuration is shown in FIG. **1**C.

UW camera **130** may include an aperture **132** (indicating object side of the camera) and an optical lens system **134** (or "Wide lens module") with a symmetry (and optical) axis **136** in the Y direction, as well as a UW image sensor **138**. The UW camera comprises a UW lens system configured to provide a UW image. As already indicated above, the UW camera has a field of view FOV_{UW} larger than the field of view of the Wide camera FOV_W. For example, FOV_{UW} may be 80-130 degrees and FOV_W may be 60-90 deg. Notably, in other examples, a plurality of Wide cameras and/or a plurality of Tele cameras can be incorporated and operative in a single digital camera. The FOV_T of a Tele camera may be for example 20-50 degrees.

Attention is now drawn to FIG. **2**A which depicts schematically an optical lens system disclosed herein and numbered **200**. Lens system **200** comprises an OPFE **202**, a lens (or "lens assembly") **204**, an optical element **206** and an image sensor **208**. System **200** is shown with ray tracing. Optical element **206** may be for example infra-red (IR) filter, and/or a glass image sensor dust cover. Optical rays (after their reflection by prism **202**) pass through lens **204** and form an image on image sensor **208**. FIG. **2**A shows 3 fields with 3 rays for each: the upper marginal-ray, the lower marginal-ray and the chief-ray. In the example of FIG. **2**A, the optical rays pass through optical element **206** before impinging on image sensor **208**. This is however not limiting, and in some examples, optical element **206** is not present, i.e. in some lens systems, the optical element is optional.

Lens **204** includes a plurality of N lens elements L_i **220** (wherein "i" is an integer between 1 and N). L_1 is the lens element closest to the object (prism) side and L_N is the lens element closest to the image side, i.e. the side where the image sensor is located. This order holds for all lenses and lens elements disclosed herein. Lens elements L_i can be used e.g. as lens elements of camera **100** above. The N lens elements are axial symmetric along an optical axis **210**. Each lens element L_i comprises a respective front surface S_{2i-1} (the index "2i−1" being the number of the front surface) and a respective rear surface S_{2i} (the index "2i" being the number of the rear surface), where "i" is an integer between 1 and N. This numbering convention is used throughout the description. Alternatively, as done throughout this description, lens surfaces are marked as "S_k", with k running from 1 to 2N. The front surface and the rear surface can be in some cases aspherical. This is however not limiting.

As used herein the term "front surface" of each lens element refers to the surface of a lens element located closer to the entrance of the camera (camera object side) and the term "rear surface" refers to the surface of a lens element located closer to the image sensor (camera image side).

In lens system **200**, a first horizontal surface of the prism (oriented along Z direction), marked as T**1**, is 10.93 mm. A second horizontal surface of the prism (oriented along the X direction, not shown) and marked T**2** is 12.6 mm. The vertical surface of the prism (along Y) marked V is 8.68 mm. The angle of the prism is 45 deg. The relatively large prism size allows for a high amount of light entering the camera, which allows the camera to have in this example a low f/# of 1.0. In other embodiments, f/# may be 0.8-1.2. The aperture stop of lens **204** is located at a distance d=−0.042 mm from S_2, i.e. from the first surface of the first lens element. For the non-zero fields shown in lens system **200**, about 80% of light reaches image sensor **208**.

As explained below, a clear height value $CH(S_k)$ can be defined for each surface S_k for 1≤k≤2N), and a clear aperture value $CA(S_k)$ can be defined for each surface S_k for 1≤k≤2N). $CA(S_k)$ and $CH(S_k)$ define optical properties of each surface S_k of each lens element. The CH term is defined with reference to FIG. **4** and the CA term is defined with reference to FIG. **5**, below.

In addition a height ("H_{Li}", for 1≤i≤N) is defined for each lens element L_i. H_{Li} corresponds, for each lens element L_i, to the maximal height of lens element L_i measured along a direction perpendicular to the optical axis of the lens elements. For a given lens element, the height is greater than, or equal to the clear height value CH and the clear aperture value CA of the front and rear surfaces of this given lens element. Typically, for an axial symmetric lens element, H_{Li} is the diameter of lens element L_i as seen in FIG. **6**. Typically, for an axial symmetric lens element, $H_{Li}=\max\{CA(S_{2i-1}), CA(S_{2i})\}$+mechanical part size.

In general, in lens design the mechanical part size is defined as not contributing to the optical properties of the lens. Because of this, one defines two heights of a lens: an optical height H_{opt} (corresponding to the CA value) of an optically active area (dotted) and a geometrical (or mechanical) height of the lens H_L which covers an optically active and an optically inactive area. The mechanical part size contribution to H_{Li} is typically 200-1000 μm.

In lens **204**, the clear aperture of the last surface S_{17} of the last lens element L_8, CA_{17}, is larger than the CA of all other surfaces S_i of the lens elements, i.e. $CA_{17}>CA_i$ for i<17. The CA of the first surface S_{16} of last lens element L_8, CA_{16}, is larger than the CA of all preceding surfaces S_i of the lens elements, i.e. $CA_{16}>CA_i$ for i<16.

In lens system **200**, N is equal to eight. This is however not limiting and a different number of lens elements can be used. According to some examples, N is equal to or greater than 7. For example, N can be equal to 7, 8, 9 or 10.

In lens system **200**, some of the surfaces of the lens elements are represented as convex, and some are represented as concave. The representation of FIG. **2**A is however not limiting and a different combination of convex and/or concave surfaces can be used, depending on various factors such as the application, the desired optical power, etc.

A lens barrel such as lens barrel **110** may carry lens **204**. In some embodiments the lens barrel may be circular such as lens barrel **110**. In other embodiments the lens barrel may be not be circular but may have a shape such as the lens elements in FIG. **7**. Referring to FIG. **7**, a non-circular lens barrel may have a X axis or a Y axis as symmetry axis. A non-circular lens barrel may e.g. be shaped according to the cut lens elements of a lens such as lens **204**'. The height of a lens barrel may be only slightly higher than the lens element having the largest height in the lens. E.g. a lens barrel may be 0-0.5 mm higher than the highest lens element. A lens barrel having an identical height as the highest lens element is described for example in co-owned international patent application PCT/IB2018/050988, which is incorporated herein by reference in its entirety.

As shown in FIGS. **3**A, **3**B and **4**, each optical ray that passes through a surface S_k (for 1≤k≤2N) impinges this surface on an impact point IP. Optical rays enter optical lens system **200** from surface S_1 and pass through surfaces S_2 to S_{2N}. Some optical rays can impinge on any surface S_k but cannot/will not reach image sensor **208**. For a given surface S_k, only optical rays that can form an image on image sensor **208** are considered. $CH(S_k)$ is defined as the distance between two closest possible parallel lines, see lines **400** and **402** in FIG. **4** located on a plane P orthogonal to the optical axis of the lens elements. In the representation of FIGS. **3**A and **3**B, plane P is parallel to plane X-Y and is orthogonal to optical axis **103** such that the orthogonal projection IP_{orth} of all impact points IP on plane P is located between the two parallel lines. $CH(S_k)$ can be defined for each surface S_k (front and rear surfaces, with 1≤k≤2N).

The definition of $CH(S_k)$ does not depend on the object currently imaged, since it refers to the optical rays that "can" form an image on the image sensor. Thus, even if the currently imaged object is located in a black background that does not produce light, the definition does not refer to this black background since it refers to any optical rays that "can" reach the image sensor to form an image (for example optical rays emitted by a background which would emit light, contrary to a black background).

For example, FIG. **3**A illustrates the orthogonal projections $IP_{orth,1}$, $IP_{orth,2}$ of two impact points IP_1 and IP_2 on plane P which is orthogonal to optical axis **103**. By way of example, in the representation of FIG. **3**A, surface S_k is convex.

FIG. **3**B illustrates the orthogonal projections $IP_{orth,3}$, $IP_{orth,4}$ of two impact points IP_3 and IP_4 on plane P. By way of example, in the representation of FIG. **3**B, surface S_k is concave.

In FIG. **4**, the orthogonal projection IP_{orth} of all impact points IP of a surface S_k on plane P is located between parallel lines **400** and **402**. $CH(S_k)$ is thus the distance between lines **400** and **402**.

Attention is drawn to FIG. **5**. According to the presently disclosed subject matter, a clear aperture $CA(S_k)$ is defined for each given surface S_k(for 1≤k≤2N) as the diameter of a circle, wherein the circle is the smallest possible circle located in a plane P orthogonal to the optical axis **108** and encircling all orthogonal projections IP_{orth} of all impact points on plane P. As mentioned above with respect to $CH(S_k)$, it is noted that the definition of $CA(S_k)$ also does not depend on the object which is currently imaged.

As shown in FIG. **5**, the circumscribed orthogonal projection IP_{orth} of all impact points IP on plane P is a circle **500**. The diameter of circle **500** defines $CA(S_k)$.

Detailed optical data and surface data are given in Tables 1-3 for the example of the lens elements in FIG. **2**A. The values provided for these examples are purely illustrative and according to other examples, other values can be used.

Surface types are defined in Table 1 and the coefficients for the surfaces are defined in Table 2:

Surface types are:

a) Plano: flat surfaces, no curvature

b) Q type 1 (QT1) surface sag formula:

$$z(r) = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2 r^2}} + D_{con}(u) \quad \text{(Eq. 1)}$$

$$D_{con}(u) = u^4 \sum_{n=0}^{N} A_n Q_n^{con}(u^2)$$

$$u = \frac{r}{r_{norm}},\ x = u^2$$

$$Q_0^{con}(x) = 1 \quad Q_1^{con} = -(5 - 6x) \quad Q_2^{con} = 15 - 14x(3 - 2x)$$

$$Q_3^{con} = -\{35 - 12x[14 - x(21 - 10x)]\}$$

$$Q_4^{con} = 70 - 3x\{168 - 5x[84 - 11x(8 - 3x)]\}$$

$$Q_5^{con} = -[126 - x(1260 - 11x\{420 - x[720 - 13x(45 - 14x)]\})]$$

where {z, r} are the standard cylindrical polar coordinates, c is the paraxial curvature of the surface, k is the conic parameter, r_{norm} is generally one half of the surface's clear aperture, and A_n are the polynomial coefficients shown in lens data tables. The Z axis is positive

TABLE 1

Lens system 200
EFL = 4.14 mm, F/# = 1.00, Diagonal FOV = 80.4 deg.

Surface #	Comment	Type	Curvature Radius	Thickness	Aperture Radius (D/2)	Material	Index	Abbe #	Focal Length
1	A.S	Plano	Infinity	−0.042	2.078				
2	Lens 1	QT1	−3.314	0.354	2.078	Plastic	1.54	55.9	26.78
3			−2.804	0.058	2.018				
4	Lens 2	QT1	11.125	0.294	2.002	Plastic	1.66	20.4	−55.77
5			8.474	0.040	2.010				
6	Lens 3	QT1	2.122	0.359	1.967	Plastic	1.65	21.5	34.22
7			2.186	0.355	2.050				
8	Lens 4	QT1	9.582	0.256	2.065	Plastic	1.67	19.4	−7.46
9			3.266	0.061	2.305				
10	Lens 5	QT1	4.164	1.565	2.357	Plastic	1.54	55.9	3.38
11			−2.887	0.219	2.481				
12	Lens 6	QT1	−3.676	1.591	2.579	Plastic	1.54	55.9	99.93
13			−3.971	0.040	2.583				
14	Lens 7	QT1	2.537	0.912	2.436	Plastic	1.67	19.4	13.54
15			3.002	0.801	2.852				

TABLE 1-continued

Lens system 200 EFL = 4.14 mm, F/# = 1.00, Diagonal FOV = 80.4 deg.									
Surface #	Comment	Type	Curvature Radius	Thickness	Aperture Radius (D/2)	Material	Index	Abbe #	Focal Length
16	Lens 8	QT1	8.867	0.354	2.974	Plastic	1.66	20.4	−8.81
17			3.479	0.259	3.285				
18	Filter	Plano	Infinity	0.210	—	Glass	1.52	64.2	
19			Infinity	0.610	—				
20	Image	Plano	Infinity	—	—				

towards image. Values for CA are given as a clear aperture radius, i.e. CA/2. The reference wavelength is 555.0 nm. Units are in mm except for refraction index ("Index") and Abbe #. Each lens element L_i has a respective focal length f_i, given in Table 1.

TABLE 2

Aspheric Coefficients					
Surface #	R_{norm}	A0	A1	A2	A3
2	1.96E+00	7.01E−01	−4.57E−02	1.03E−02	−9.49E−04
3	1.98E+00	8.98E−01	−9.70E−02	1.92E−02	−5.01E−03
4	1.96E+00	−7.58E−02	−8.16E−02	1.72E−02	1.98E−03
5	1.90E+00	−2.09E−01	−2.62E−02	7.39E−03	2.93E−03
6	1.76E+00	−6.48E−01	−4.85E−02	−2.11E−03	−1.95E−03
7	1.79E+00	−7.12E−01	−5.06E−02	4.56E−03	−4.47E−04
8	1.80E+00	−2.24E−01	−7.75E−03	7.30E−03	−1.86E−03
9	1.84E+00	−2.52E−01	1.46E−02	2.39E−03	−3.73E−03
10	1.98E+00	−1.56E−01	−3.39E−04	1.13E−03	−7.45E−04
11	2.04E+00	5.32E−01	−7.05E−02	6.97E−03	3.13E−04
12	2.14E+00	8.97E−01	−1.12E−01	1.97E−02	−2.85E−03
13	2.09E+00	1.58E−02	2.61E−02	−4.19E−03	7.93E−04
14	2.13E+00	−7.72E−01	−5.12E−02	−1.16E−02	−6.42E−04
15	2.63E+00	−1.11E+00	−1.05E−01	4.11E−02	−2.53E−05
16	2.73E+00	−9.92E−01	1.86E−01	2.37E−02	−1.12E−02
17	3.20E+00	−2.04E+00	1.88E−01	−6.16E−02	−2.74E−02
Surface #	A4	A5	A6	A7	A8
2	1.37E−04	3.42E−05	1.55E−06	0.00E+00	0.00E+00
3	8.19E−04	−1.08E−04	5.14E−06	0.00E+00	0.00E+00
4	−8.58E−04	5.69E−05	−2.90E−04	0.00E+00	0.00E+00
5	−1.76E−03	5.55E−04	−2.96E−04	0.00E+00	0.00E+00
6	−7.14E−04	1.16E−04	3.39E−05	0.00E+00	0.00E+00
7	−2.33E−04	−4.64E−05	2.51E−05	0.00E+00	0.00E+00
8	8.01E−04	−2.83E−04	1.97E−05	0.00E+00	0.00E+00
9	1.36E−03	−2.35E−04	1.55E−05	0.00E+00	0.00E+00
10	6.24E−04	−1.91E−04	1.83E−05	0.00E+00	0.00E+00
11	−2.57E−04	6.98E−05	−5.72E−06	0.00E+00	0.00E+00
12	3.28E−04	−1.68E−05	−7.24E−07	0.00E+00	0.00E+00
13	−1.38E−04	2.67E−05	−2.84E−06	0.00E+00	0.00E+00
14	−4.12E−04	3.26E−04	−2.63E−04	1.47E−04	−3.10E−05
15	4.72E−03	−3.18E−03	7.16E−05	−2.80E−04	1.03E−04
16	7.44E−03	−5.47E−03	4.68E−04	3.29E−04	−3.43E−05
17	1.30E−02	−4.97E−03	2.36E−03	−2.23E−03	4.96E−04

In the example of FIG. **2**A, the following optical properties are achieved:

TTL=8.34 mm

BFL=1.08 mm

EFL=4.14 mm

$$CA(S_{17}) > CA(S_k),\ 1 < k \leq 2N$$

$$CA(S_{16}) > CA(S_k),\ 1 < k \leq 2N-1$$

$$CA(S_{15}) > CA(S_k),\ 1 < k < 2N-2$$

f/#=1.0

Sensor diagonal (SD) is 7 mm, sensor width/height ratio is 4:3

Minimum CA/SD ratio: $CA(S_4)/SD=0.57$

Maximum CA/SD ratio: $CA(S_{17})/SD=0.94$

Diagonal FOV=80.44 deg, Horizontal FOV=68.32 deg, Vertical FOV=53.48 deg,

Distance d from aperture stop to S_2: d=−0.042 mm

L_1, L_2 and L_3 have relatively low power (magnitude), so $|f_i|>5\cdot EFL$ for $1\leq i\leq 3$

L_4 and L_5 together have positive power, so for the lens sub-system including L_4 and L_5 at a thickness d apart from each other and as given in Table 1 which has focal length $1/(f_4+f_5)=[1/f_4+1/f_5-d/(f_4 f_5)]>0$

For L_5 yields: $f_5<EFL$

L_4 and L_5 satisfy: $|f_4|<3\times f_5$

Minimal gap between L_4 and L_5: Gap_{Min}=0.04 mm

Maximal gap between L_4 and L_5: Gap_{Max}=0.0745 mm

Average gap AVG_4 between L_4 and L_5: AVG_4=0.048 mm

STD_4 from average gap $AVG_4(r)$ between L_4 and L_5: $STD_4=3.42\cdot 10^{-3}$ mm.

Lens **204** may be carried by a lens barrel having a lens barrel height of e.g. 6.57 mm-7.2 mm.

In this specification, a "gap" or an "air gap" refers to the space between consecutive lens elements. In the case of lens elements **4** and **5**, "gap" refers to the air space between the last surface of L_4 and the first surface of L_5.

A number of functions and constants per gap are defined:

1. A "$Gap_i(r)$" function, (where i is the lens element number and r is the same variable used in Eq. 1) is:

a) for i=1: $Gap_1(r)=z(r)$ of L_2S_1+(the distance along the second optical axis between the prism exit surface and L_2S_1);

b) for i>1: $Gap_i(r)=z(r)$ of $L_{i+1}S_1$+(the distance along the second optical axis between L_iS_2 and $L_{i+1}S_1$)−z(r) of L_iS_2;

c) for r=0, an "on-axis gap" (OA_Gap_i) is defined as $Gap_i(r=0)$;

2. A "gap average" (AVG_i) constant is given by:

$$AVG_i = \frac{1}{N+1/2}\sum_{j=0}^{N} Gap_i\left(\frac{j \cdot r_{norm}}{N}\right) \quad \text{(Eq. 2)}$$

where j is a discrete variable that runs from 0 to N, where N is an integer >10, and where r_{norm} is the minimum value D/2 of surfaces $\{L_iS_2, L_{i+1}S_1\}$.

3. A normalized gap standard deviation (STD_i) constant is given by:

$$STD_i = \frac{1}{r_{norm}}\sqrt{\frac{1}{N-1/2}\sum_{j=0}^{N}\left(Gap_i\left(\frac{j \cdot r_{norm}}{N}\right) - AVG_i\right)^2} \quad \text{(Eq. 3)}$$

where r_{norm} is the minimum value D/2 of surfaces $\{L_iS_2, L_{i+1}S_1\}$, N is an integer >10, and AVG_i is defined as in (Eq.2).

Attention is now drawn to FIG. **2**B, which depicts schematically another optical lens system disclosed herein and numbered **200**'. Lens system **200**' comprises an OPFE **202**, a lens **204**' with a plurality of lens elements, an optical element **206** and an image sensor **208**. Ray tracing is provided as in FIG. **2**A. Detailed optical data and surface data are given in Tables 1 and 2. However, data on aperture radius for all surfaces of L_6 and L_8 as well as surface S_{15} of L_7 is to be replaced by 2.5 mm in the y-direction (no change in x-direction).

For achieving a folded lens system with low f/# and low lens height at the same time, lens elements are cut to a non-circular shape (often called "cut lens" or "D cut lens"). The lens elements are obtained by cutting the large lens elements of lens **204**' to a height of 5 mm (in the Y direction). That is, the lens elements L_i of lens **204**' that have height H_{Li}>5 mm (i.e. L_6, L_7 and L_8) are cut to 5 mm. The cut lens elements have no circular symmetry like that of lens elements **204**, but their width is larger than their height, i.e. $W_{Li}>H_{Li}$ (see example in FIG. **7**). The lens elements Li of lens **204** that have height $H_{Li}\leq 5$ mm are not changed. As of the cut, lens elements L_6, L_7 and L_8 have a large CA but still low CH. This is beneficial as in a folded lens design a lens height H_L may determine the camera's height, wherein the camera height is generally limited by a height of the host device. A lens having large CA and low CH is beneficial for a low f/# folded lens that is compatible with e.g. a smartphone's height constraints. Lens elements of lens **204**' are cut in direction Y, meaning that the height of a lens element H_{Li} is smaller than its width W_{Li}. The CA of lens elements L_1-L_5 may be oriented in any direction, e.g. in Y direction. As of the cut design, the CA of lens element L_6, L_7 and L_8 is oriented in X direction (not shown here). In other embodiments, only one or only two lens elements L_i may be cut, i.e. may have $W_{Li}>H_{Li}$. In yet other embodiments, more than 3 lens elements L_i may be cut, i.e. may have $W_{Li}>H_{Li}$. In yet other embodiments, all lens elements L_i may be cut, i.e. may have $W_{Li}>H_{Li}$. In other embodiments, lens **204**' may be achieved by cutting the large lens elements of lens **204** to a height of e.g. 4.5 mm or 4 mm (in the Y direction), i.e. the lens elements L_i that have height H_{Li}>4.5 mm (i.e. L_4, L_5, L_6, L_7 and L_8) or 4 mm (i.e. L_1-L_8) may be cut to 4.5 mm or 4 mm respectively. In yet other embodiments, lens **204**' may formed by cutting the large lens elements of lens **204** to a height of e.g. 3.5 mm or 3 mm (in Y direction).

In lens system **200**', the prism dimensions are identical with those in lens system **200**: T**1**=10.93 mm, T**2**=12.6 mm and V=8.68 mm.

Besides the properties described in FIG. **2**A, in the example of FIG. **2**B, the following optical properties are achieved:

$$CA(S_{12}) = 1.03 \times CH(S_{12}) = 2.58 \text{ mm}$$

$$CA(S_{13}) = 1.03 \times CH(S_{13}) = 2.58 \text{ mm}$$

$$CA(S_{15}) = 1.14 \times CH(S_{15}) = 2.85 \text{ mm}$$

$$CA(S_{16}) = 1.19 \times CH(S_{16}) = 2.97 \text{ mm.}$$

$$CA(S_{17}) = 1.32 \times CH(S_{12}) = 3.29 \text{ mm}$$

$$CA(S_{17}) > CA(S_k),\ 1 < k \leq 2N.$$

$$CA(S_{16}) > CA(S_k),\ 1 < k \leq 2N-1$$

$$CA(S_{15}) > CA(S_k),\ 1 < k < 2N-2$$

For all lens surfaces $CH(S_k)\leq 5$ mm

f/#=1.0

Minimum CA/SD ratio: $CA(S_4)$/SD=0.57

Maximum CA/SD ratio: $CA(S_{17})$/SD=0.71

Lens **204**' may be carried by a lens barrel having a lens barrel height of e.g. 5.0 mm-5.5 mm.

FIG. **2**C depicts schematically another optical lens system disclosed herein and numbered **200**". Lens system **200**" comprises an OPFE **202**', lens **204**, an optical element **206** and image sensor **208**. Ray tracing is provided as in FIG. **2**A. Detailed optical data and surface data are given in Tables 1 and 2. In comparison with the OPFEs shown in FIG. **2**A and FIG. **2**B, OPFE **202**' has a smaller prism height ("V") of 7.82 mm. The smaller prism height may be beneficial for achieving a slim folded camera.

Here T**1**=9.815 mm, T**2**=12.6 mm and V=7.82 mm. For the non-zero fields of lens system **200**", the reduction of light compared to optical lens systems **200** and **200**' is 8% or less. For the zero fields there is no change in the amount of light entering the camera. The high amount of light entering the camera allows for the camera's low f/# of 1.0. In other embodiments a f/# may be 0.8-1.2.

FIG. **2**D depicts schematically yet another optical lens system disclosed herein and numbered **200**'". Lens system **200**'" comprises an OPFE **202**", lens **204**, optical element **206** and image sensor **208**. Ray tracing is provided as in FIG. **2**A. Detailed optical data and surface data are given in Tables 1, 2. In comparison with OPFE **202**' shown in FIG. **2**C, OPFE **202**" has a smaller prism height ("V") of 7.02 mm.

Here T**1**=8.75 mm, T**2**=12.6 mm and V=7.02 mm. For the non-zero fields of lens system **200**'" the reduction of light compared to lens systems **200** and **200**' is 19% or less. For the zero fields there is no change in the amount of light entering the camera. The high amount of light entering the camera allows for the camera's low f/# of 1.0. In other embodiments, f/# may be 0.8-1.2.

FIG. **2**E depicts schematically yet another optical lens system disclosed herein and numbered **200**"". Lens system **200**"" comprises an OPFE **202**'", lens **204**", optical element **206** and image sensor **208**. Ray tracing is provided as in FIG. **2**A. Detailed optical data and surface data are given in Tables 1, 2. However, data on aperture radius for all surfaces of L_6, and L_5 as well as of surfaces S_{11} of L_5 and S_{15} of L_7 is to be replaced by 2.45 mm in y-direction (no change in x-direction). The prism height (measured along the Y-axis) is larger than the height of lens **204**". The height of the entire lens system **200**"" (measured along the Y-axis) is determined solely by the prism height, i.e. there is no additional "height penalty" introduced by lens **204**".

In comparison with OPFE **202**" shown in FIG. **2**D, OPFE **202**"' has a smaller prism height of 6.00 mm.

The lens elements of lens **204**" are obtained by cutting the large lens elements of lens **204**" to a height of 4.9 mm (in Y direction). That is, the lens elements L_i of lens **204**" that have height H_{Li}>4.9 mm (i.e. L_6, L_7 and L_8) are cut to 4.9 mm. The cut lens elements have no circular symmetry like that of lens elements **204**, but their width is larger than their height, i.e. $W_{Li}>H_{Li}$ (see example in FIG. **7**). In other embodiments, lens **204**" may be achieved by cutting the large lens elements of lens **204** to a height of e.g. 4.5 mm or 4 mm (in the Y direction), i.e. the lens elements L_i that have height H_{Li}>4.5 mm (i.e. L_4, L_5, L_6, L_7 and L_8) or 4 mm (i.e. L_1-L_8) may be cut to 4.5 mm or 4 mm respectively.

Further explanation on cut lenses is provided in description of FIG. **2**B. Here T**1**=6.95 mm, T**2**=12.6 mm and V=6.00 mm. For the non-zero fields shown in lens system **200**"", about 55%-60% of light reaches image sensor **208**. For the non-zero fields of lens system **200**"" the reduction of light compared to the respective non-zero fields of lens systems **200** and **200**' is about 30%. The light reduction is primarily caused by the smaller prism dimensions, not by the D cut of the larger lens elements. The light reduction occurs symmetrically for the upper marginal-ray and the lower marginal-ray. The difference in the amount of light that reaches image sensor **208** for the D cut lens in lens system **200**"" and a non D cut lens amounts to <5%. For the zero fields there is no change in the amount of light entering the camera. The high amount of light entering the camera allows for the camera's low f/# of 1.0. In other embodiments, f/# may be 0.8-1.2. Lens **204**" may be carried by a lens barrel having a lens barrel height of e.g. 4.9 mm-5.5 mm.

According to some examples, at least part of the lens elements can have a shape (profile) in cross-section (in plane X-Y, which is orthogonal to the optical lens system and which generally coincides with the optical axis) which is not circular. In particular, as shown e.g. in FIG. **7**, at least some of the lens elements which are integrated in lens barrel **710** can have a width W_{Li} (measured along axis X) which is greater than their height H_{Li} (measured along axis Y). The height H_{Li} can correspond to the total height of the lens element (including the mechanical part). In some embodiments, a lens element in lens system **700** may have a symmetry about axis Y and/or about axis X.

According to some examples, W_{Li} is substantially greater than H_{Li} (for example, by at least a percentage that is equal or greater than 20%, these values being not limiting). In some examples, W_{Li} may be greater than H_{Li} by a percentage of 20-70%. Consider lens element L_8 of folded lens **204**' as an example: W_{L8} is greater than H_{L8} by a percentage of 32%. Another example is lens element L_8 of folded lens **204**": W_{L8} is greater than H_{L8} by a percentage of 44%.

Unless otherwise stated, the use of the expression "and/or" between the last two members of a list of options for selection indicates that a selection of one or more of the listed options is appropriate and may be made.

It should be understood that where the claims or specification refer to "a" or "an" element, such reference is not to be construed as there being only one of that element.

All patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present disclosure.

What is claimed is:

1. A folded camera, comprising: a lens having an effective focal length (EFL) and including N≥7 lens elements L_i along a lens optical axis wherein a first lens element L_1 faces an object side, wherein each lens element Li has a respective front surface S_{2i-1} and a respective rear surface S_{2i}, the lens element surfaces marked S_k where 1≤k≤2N, wherein each lens element surface S_k has a clear height value $CH(S_k)$ and a clear aperture value $CA(S_k)$, and wherein a clear aperture value $CA(S_{2N})$ in lens element L_N is greater than a clear aperture value $CA(S_1)$ in lens element L_1;

an image sensor; and

an optical path folding element (OPFE) for folding a first optical path to a second optical path that is perpendicular to the first optical path and parallel to the lens optical axis, wherein one or more of the lens elements are cut lens elements that have a respective width W_{Li} measured along an axis perpendicular to both the first optical path and the second optical path, and a respective height H_{Li} measured along an axis parallel to the first optical path, wherein $W_{Li}>H_{Li}$, wherein the camera has an f number f/#<1.1, and

wherein the folded camera is a wide camera with a field of view (FOV) ranging from 60 degrees to 90 degrees.

2. The folded camera of claim **1**, wherein f/#≤1.0.

3. The folded camera of claim **1**, wherein in at least one of the cut lens elements $W_{Li}/H_{Li}>1.1$.

4. The folded camera of claim **1**, wherein in at least one of the cut lens elements $W_{Li}/H_{Li}>1.2$.

5. The folded camera of claim **1**, wherein a clear height value of all lens elements is smaller than or equal to 5 mm.

6. The folded camera of claim **5**, wherein the lens is included in a lens barrel, wherein the lens barrel has a lens barrel height measured along the first optical path, and wherein the lens barrel height is smaller than or equal to 5.5 mm.

7. The folded camera of claim **1**, wherein the camera has a diagonal field of view (FOV) larger than 60 degrees.

8. The folded camera of claim **1**, wherein the image sensor lies in a plane that is parallel to the first optical path.

9. The folded camera of claim **1**, wherein the folded camera has a total track length (TTL), and wherein an aperture stop of the lens is located closer to a first surface S_1 of lens L_1 than a distance d that fulfills d/TTL=0.2.

10. The folded camera of claim **1**, wherein the image sensor has a sensor diagonal SD>6 mm.

11. The folded camera of claim **1**, wherein the OPFE has a height H_O, wherein the lens has a height H_L, wherein H_O and H_L are measured along a direction parallel to the first optical path, and wherein $H_O>H_L$.

12. The folded camera of claim **6**, wherein the OPFE has a height H_O, wherein the lens barrel has a height H_{LB}, wherein H_O and H_{LB} are measured along a direction parallel to the first optical path, and wherein $H_O>H_{LB}$.

13. The folded camera of claim **1**, wherein the camera has a height H_C and the OPFE has a height H_O, wherein H_O and H_C are measured along a direction parallel to the first optical path, and wherein H_C is determined by H_O.

14. The folded camera of claim **1**, wherein an absolute value of an optical power of element $L_i|f_i|>5\times EFL$ for $1\leq i\leq 3$.

15. The folded camera of claim **1**, wherein lens element L_5 has a strongest optical power of all lens elements $|f_5|<|f_i|$ for $i\neq 5$.

16. The folded camera of claim **1**, wherein STD is a normalized air gap standard deviation of an air gap between two consecutive lens elements, and wherein the lens includes at least one air gap between lens elements that complies with the condition STD<0.020.

17. The folded camera of claim **1**, wherein the folded camera is included in a mobile device.

18. The folded camera of claim **17**, wherein the mobile device is a smartphone.

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