



(51) International Patent Classification:

G06T 7/557 (2017.01) G02B 27/00 (2006.01)
G06T 7/521 (2017.01) G02B 5/18 (2006.01)

(21) International Application Number:

PCT/KR2022/016053

(22) International Filing Date:

20 October 2022 (20.10.2022)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

2021137160 15 December 2021 (15.12.2021) RU

(71) Applicant: **SAMSUNG ELECTRONICS CO., LTD.**
[KR/KR]; 129, Samsung-ro, Yeongtong-gu Suwon-si,
Gyeonggi-do 16677 (KR).

(72) Inventors: **OSIPOV, Alexey Aleksandrovich**; Office
#1500, 12 Dvintsev Street, Korpus 1, Moscow, 127018
(RU). **KOPYSOVA, Tatiana Igorevna**; Office #1500,
12 Dvintsev Street, Korpus 1, Moscow, 127018 (RU).
SHLYAPIN, Alexander Sergeevich; Office #1500, 12
Dvintsev Street, Korpus 1, Moscow, 127018 (RU).
PISKUNOV, Dmitriy Evgenyevich; Office #1500, 12 Dv-
intsev Street, Korpus 1, Moscow, 127018 (RU). **PETRO-
VA, Ksenia Yurievna**; Office #1500, 12 Dvintsev Street,
Korpus 1, Moscow, 127018 (RU).

(74) Agent: **LEE, Keon-Joo** et al.; Mihwa Bldg., 16, Daehak-ro
9-gil, Chongro-gu, Seoul 03079 (KR).

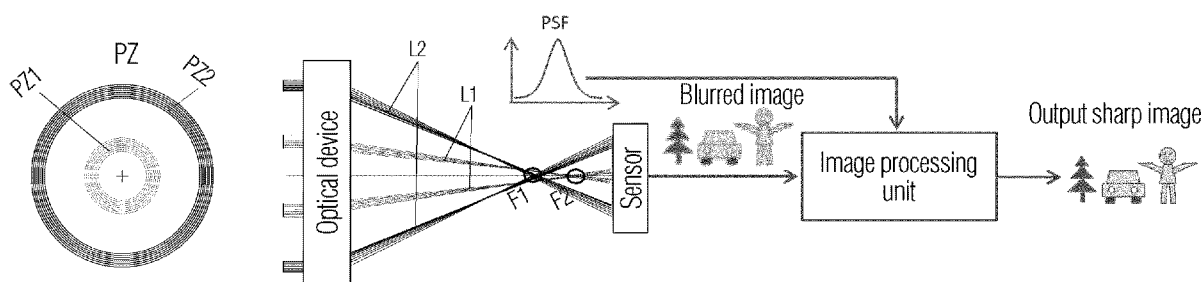
(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE,
KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU,
LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG,
NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS,
RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH,
TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS,
ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, CV,
GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI,
SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN,
GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: DEVICE AND METHOD FOR EXTENDED DEPTH OF FIELD IMAGING



(57) Abstract: The invention relates to a device and method for extended depth of field imaging, the device comprising: an optical unit configured to simultaneously form intermediate images of an object at different distances with a blur effect on at least parts of the object images, and comprising at least one optical element, and having at least two pupil zones formed to provide a predetermined distribution of optical powers and aberrations within each of the at least two pupil zones, based on which point spread function is formed, defined by a curve with minimized side peaks compared to central peak in given range of object distances, each of the at least two pupil zones corresponding to a respective given range of object distances and respective given range of field angles; a sensor configured to simultaneously register intermediate images formed by the optical unit from different object distances and at different field angles; an image processing unit connected to the sensor and configured to process the blurred intermediate images of at least parts of the object images registered by the sensor, said images being processed based on the obtained point spread function over the given range of distances and field angles, and reconstruct resulting images without a blur effect at output regardless of object distances.



Description

Title of Invention: DEVICE AND METHOD FOR EXTENDED DEPTH OF FIELD IMAGING

Technical Field

- [1] The invention relates to methods and devices for extended depth of field imaging, and can be used, in particular, for capturing photo and video with smartphone cameras, and in tablet computers running Android, iOS, HarmonyOS and similar operating devices, and in other similar devices requiring the provision of extended depth of field.

Background Art

- [2] A variety of imaging means exist in the art which provide extended depth of field.
- [3] The following patent publications can be related to this group.
- [4] An imaging system with optimized extended depth of focusing is disclosed in application US20190212478A1, publ. 11.07.2019, IPC G02B3/00, wherein an optical processor comprises a pattern in the form of spaced apart regions of different optical properties. The pattern is configured to define two phase masks in the form of a phase coder and a dispersion profile coder. The phase coder affects profiles of modulation transfer function (depending on defocusing), increasing depth of focusing of the lens unit; as a result wavelength components of the transfer function are shifted relative to each other. The dispersion profile coder compensates for this shift. Drawbacks of this disclosure include a lot of optical components in the imaging system, particularly: an imaging lens unit, two phase masks, which affect quality of the image produced. Furthermore, as clearly illustrated in the plot of Fig. 4B of US20190212478, the transfer function profile obtained in the system is nonuniform, which makes subsequent image processing difficult; in addition no means for deblurring the resulting image are disclosed.
- [5] US7593161B2, publ. 22.09.2009, IPC G02B 5/02, discloses an apparatus and method for extended depth of field imaging. Extended depth of field is achieved by a computational imaging system that combines a multifocal imaging subsystem for producing a blurred intermediate image with a digital processing subsystem for producing a recovered image having an extended depth of field. The multifocal imaging system preferably exhibits spherical aberration as the dominant feature of the purposeful blur. A central obscuration of the multifocal imaging subsystem renders point spread functions of object points more uniform over a range of object distances. An iterative digital deconvolution algorithm for converting the intermediate image into the recovered image contains a metric parameter that increases the algorithm efficiency and enhances image quality. Drawbacks of this disclosure include a lot of optical

components in the multifocal imaging system, which affect the resulting image quality. Furthermore, only spherical aberration is used to increase the depth of field, and no image processing means are provided to deblur the image produced.

- [6] US7616842B2, 10.11.2009, IPC G06K7/00, discloses a method and system for designing an imaging system including an optical subsystem, a detector subsystem and a digital image processing subsystem that includes at least one digital filter; the method comprises predicting end-to-end imaging performance using a spatial model for the source and models for the optical subsystem, the detector subsystem and the digital image processing subsystem. The optical subsystem and digital image processing subsystems are jointly designed taking into account characteristics of the entire system. The intermediate image produced by the optical subsystem is not required to be high quality since the quality may be corrected by the digital image processing subsystem.
- [7] However this solution provides a design method, rather than an optical system for extended depth of field imaging (EDoF).
- [8] US11022815B2, publ. 01.06.2021, IPCG02C 7/02, discloses systems and methods for providing improved image quality across a wide and extended range of foci, which encompass vision treatment techniques and ophthalmic lenses such as contact lenses and intraocular lenses (IOLs). IOL includes a first and second lens surfaces. The first or second lens surface represents a refractive surface with an aspheric profile or diffractive profile. The refractive surface with aspheric profile can focus light toward a far focus. The surface with diffractive profile can include a central zone that distributes a first percentage of light toward a far focus and a second percentage of light toward an intermediate focus. The diffractive profile can also include a peripheral zone, surrounding the central zone, which distributes a third percentage of light toward the far focus and a fourth percentage of light toward the intermediate focus. The disclosure is intended for medical use only in contact and intraocular lenses and does not provide for image processing means to deblur the image produced.
- [9] US5715031A, publ. 03.02.1998, IPC G02C7/04, discloses concentric aspheric multifocal lens designs which use a combination of an aspheric front surface, which results in aberration reduction and contrast vision enhancement, along with a concentric multifocal back surface, to produce a lens design which affords clear vision at a distance and also near without a loss in contrast. The aspheric surface improves the modulation transfer function (MTF) of the lens eye combination which improves the focus and contrast of both distance and near images. The designs are intended for medical use only in contact and intraocular lenses and does not provide for an image processing means to deblur the produced image.
- [10] US8985767B2, publ. 24.03.2015, IPC G02C 7/02, discloses a method for designing a progressive lens, including: obtaining a wavefront measurement of an eye, determining

an initial design for the progressive lens based on the wavefront measurement, determining information about how changes in one or more higher order aberrations of the eye affect a second order correction for the aberrations of the eye based on information derived from the wavefront measurement. The obtained information is used for modifying the initial design of the progressive lens to provide a final progressive lens design, and outputting the final lens design. The disclosure is intended for medical use only for eye correction, and does not relate to systems for extended depth of field.

- [11] A patent application EP01865827, publ. 19.12.2007, IPC A61B 3/103, discloses a method and device for modifying optical system properties by means of a continuous multifocal profile, wherein said profile comprises a component for increasing the optical system focal depth, and is computed according to a fourth-order Zernike polynomial. To avoid the eye base refraction, said focal depth increasing component is also computed according to the second-order Zernike polynomial. The disclosure is intended for medical use only for contact lenses and intraocular lenses, and only fourth-order and second-order Zernike polynomials are used, but no deblur system is provided for the image produced.
- [12] JP2011232606, publ. 17.11.2011, IPC G01B 11/24, discloses a camera, an optical system, and interchangeable lens with birefringent device. The birefringent device is adapted to selectively attenuate the side peak (side lobes) in the out-of-focus point spread function of the lens unit. This optical system requires additional optical units, in particular a birefringent device, which significantly increases its cost.
- [13] Optical system with extended depth of field, disclosed in US8559118, publ. 15.10.2013, IPC G02B 13/18, is regarded as the closest prior art of the present invention. The optical system yields an asymmetric modulation transfer function (MTF). In some aspects, the asymmetric MTF results in extended depth of field for near field objects. The optical system comprises a set of lenses (e.g. four lenses or five lenses): a first lens having a positive refractive power, with both the surface facing the object side and the surface facing the image side having convex shapes; a second lens having a negative refractive power and a meniscus shape, with the surface facing the object side having a concave shape near the optical axis and the surface facing the image side having a convex shape near the optical axis; a third lens; and a fourth lens having a meniscus shape near the optical axis, with the surface facing the object side having a convex shape near the optical axis and the surface facing the image side having a concave shape near the optical axis. The length of the optical system remains below about 5.3 mm. The optical systems can be used for a high resolution compact camera, for example, in combination with an electronic computing device, a communication device, a display device, surveillance equipment, or the like. In this device, special lens shapes are used, and the inventors thereby try to provide the required

optical characteristics of the device. However, operating only with the shape of the lenses, it is not possible to obtain invariant optical characteristics depending on the object distance. Drawback of this optical system is a small depth of field and nonuniform modulation transfer function depending on out-of-focus position.

[14] As opposed to the closest prior art (US8559118), where a specific lens shape is used for extended depth of field, the inventive imaging device uses a multizone optical unit with each zone working at its own depth. The prior art optical system forms point spread function with side lobes, which leads to image distortions of far point objects: they are formed with ring or half ring-shape halos. The present multizone optical device overcomes this problem. Moreover, although the closest prior art provides for the presence of an image processing unit, details of its implementation and operation algorithm are not disclosed in US8559118. The inventors of the present invention use an image processing unit to reconstruct a blurred intermediate image based on the Point Spread Function (PSF) or modulation transfer function (MTF) of the optical imaging device, and parameters of the optical unit and the image processing unit are computed jointly using end-to-end optimization methods.

[15] [Prior Art]

[16] A - Conventional technical solutions (US11022815B2, US5715031A, US8985767, EP01865827B1, used in ophthalmology):

[17] 1) provide vision correction, create image on retina;

[18] 2) are used in contact lenses, IOLs and eyeglasses;

[19] 3) comprise an imaging system, which is a single lens working together with the eye;

[20] 4) focal length of the imaging system is generally over 150 mm;

[21] 5) optical unit comprises single lens only and no image processing is provided;

[22] 6) form image at far and near distances, which requires accommodation of the user's eye.

[23] B - Conventional solutions (US20190212478, US7593161, US8559118, used in systems for extended depth of field imaging).

[24] 1) optical system has a lot of optical parts (special-shaped lenses, phase masks,) that make up the imaging system, which affect quality of the image being formed and the system cost;

[25] 2) obtained modulation transfer function (MTF) profile is nonuniform, which makes subsequent image processing difficult;

[26] 3) optical system forms point spread function (PSF) with side lobes, which leads to image distortions of far point objects (they are formed with ring-shaped halos);

[27] 4) no image processing unit is provided, or if provided, aspects of its operation algorithm in conjunction with optical system are not disclosed.

Disclosure of Invention

Technical Problem

- [28] Therefore, the inventors have developed a method and system for extended depth of field imaging, which overcome drawbacks of aforementioned prior art disclosures.
- [29] The object of the present invention is to provide a method and device for extended depth of field imaging.
- [30] Furthermore, the inventors have developed a method and device that eliminate drawbacks of conventional methods for extended depth of field imaging and offer the following advantages:
- [31] Optical system for smartphone's camera with extended depth of field (EDoF) without autofocus;
- [32] - No focusing delay
- [33] - Fast reconstruction algorithm
- [34] - No need of user interaction (no need to select a focus area)
- [35] - Cheap, compact optical unit of the inventive imaging device, applicable for mass-production.
- [36] Therefore, the object of the present invention is to provide a method and device for extended depth of field imaging without additional optical elements, forming high-quality images after processing by artificial neural networks using point spread function information.
- [37] Main challenges of conventional designs in the field of smartphone cameras:
- [38] - conventional autofocus cameras use moving parts, such as an electromagnetic drive to move camera lens relative to the sensor, which leads to autofocus delay and bulky design;
- [39] - existing cameras without autofocus apply additional optical elements, such as phase plates, to provide extended depth of field, which leads to additional manufacturing costs.
- [40] It should be noted that conventional autofocus systems have moving mechanical parts (motor, cam, gear) for lens displacement to focus on the object, which leads to focusing delay and affects quality of capturing fast moving objects. In addition, in some autofocus systems (AF systems), user interaction is required to manually select focus area and adjust focus position to avoid possible autofocus errors.
- [41] Moreover, in conventional AF systems, when pointed at a target object and forming sharp image of the object, unnatural blurred background image in the form of oval, ring or semi-ring halos (donut-shape bokeh) is observed.

Solution to Problem

- [42] According to a first aspect of the invention there is provided a device for extended

depth of field imaging, comprising:

- [43] an optical unit configured to simultaneously form intermediate images of an object at different distances with a blur effect on at least parts of the object images, and containing at least one optical element, and having at least two pupil zones formed to provide a predetermined distribution of optical powers and aberrations within each of the at least two pupil zones, based on which point spread function is formed, defined by a curve with minimized side peaks compared to central peak in given range of object distances, each of the at least two pupil zones corresponding to a respective given range of object distances and respective given range of field angles;
- [44] a sensor configured to simultaneously register intermediate images formed by the optical unit from different object distances and at different field angles;
- [45] an image processing unit connected to the sensor and configured to process the blurred intermediate images of at least parts of the object images registered by the sensor, said images being processed based on the obtained point spread function over the given range of distances and field angles, and reconstruct resulting images without a blur effect at output regardless of object distances.
- [46] Moreover, the minimized side peaks of the point spread function, formed by the optical unit, do not exceed 10% of the central peak in the given range of object distances.
- [47] According to the invention, the given range of object distances is from 400 mm to 5000 mm, and the given range of field angles is from -40 to +40 degrees.
- [48] Furthermore, the optical unit is configured to form invariant point spread function independent of object distance over the given range, or independent of field angle, or independent of field angle and object distance.
- [49] The optical unit can be configured to form uniform modulation transfer function (MTF) independent of object distance.
- [50] Furthermore, the optical unit can be configured to simultaneously form intermediate images of the object at different distances with a blur effect on the entire image of the object, and comprises at least one optical element, which is at least one of: lens with different surface profiles, composite lens, diffractive optical element, holographic optical element, polarizing element, amplitude-phase mask.
- [51] One or more lenses of the optical unit can have aspheric surface and/or in particular Zernike surface, which provide aberration correction.
- [52] Moreover, according to an embodiment of the invention, optical elements of the optical unit comprise, arranged along the optical axis from the object side toward the image surface, a first lens, a second lens, a third lens, a fourth lens, a fifth lens and a sixth lens, where
- [53] the first lens has a positive refractive power, with the surface facing the object side

- having a convex shape and the surface facing the image side having concave shape;
- [54] the second lens has a negative refractive power and with both the surface facing the object side and the surface facing the image side having concave shape;
- [55] the third lens has a positive refractive power,
- [56] the fourth lens has a meniscus shape,
- [57] each of the fifth and sixth lenses has a meniscus shape near the optical axis, with the surface each of the fifth and sixth lenses facing the object side having a convex shape near the optical axis and the surface each of the fifth and sixth lenses facing the image side having a concave shape near the optical axis.
- [58] Moreover, in the optical unit, the composite lens is at least one of: a bifocal lens, a progressive lens, a Fresnel lens, and/or combinations thereof; the diffractive optical element is a diffractive microstructure designed to provide amplitude-phase modulation of transmitted or reflected light; the holographic element is designed and arranged to contribute to elimination of chromatic aberrations.
- [59] Moreover, the polarizing element is a polarizer and/or a phase plate and/or a polarizing filter, wherein the polarizing element, such as a polarizer and/or a phase plate, is configured to ensure multiple passage of light through optical elements of the optical unit, and the polarizing element comprises a polarizing filter configured to eliminate glare.
- [60] It should be noted that in the device according to the invention the amplitude-phase mask is made and arranged in the optical unit to provide a phase delay or amplitude modulation of light to ensure uniform modulation transfer coefficient over required image depth, and the amplitude-phase mask is one of: a fourth-degree parabola phase profile mask, a cubic phase mask, a mask with concentric annular holes in the screen.
- [61] Moreover, each optical element of the optical unit is made of an optically transparent material selected from at least one of: optical glass, optical crystal and polymer.
- [62] The device according to the first aspect of the invention can comprise a shutter disposed in the plane of aperture diaphragm or the imaging device plane conjugate with it, and the shutter is configured to control opening or closing of given number of pupil zones.
- [63] The sensor is a matrix photodetector, in particular, a CMOS matrix photodetector or a CCD sensor, configured to detect electromagnetic radiation in the range of 0.4 - 0.7 μm , and the sensor pixel size is from 0.7 μm to 1.5 μm .
- [64] The image processing unit is configured to process intermediate images of the object and reconstruct resulting images at output based on a convolutional neural network and/or Wiener filter, parameters of which are predetermined based on design parameters of the optical unit and the sensor.
- [65] Parameters of the optical unit include at least one of: radii of surfaces of the optical

elements, coefficients of aspheric surfaces of the optical elements, thicknesses of the optical elements, refractive indices of materials of the optical elements, amount of dispersion of the optical elements, distances between optical elements in the optical unit, device length representing axial distance between surface of the first optical element on the object side and image surface on the sensor, and parameters of the sensor include at least one of: spectral sensitivity, noise, sampling parameters.

[66] According to a second aspect of the invention there is provided a device for extended depth of field imaging, comprising:

[67] an optical unit configured to simultaneously form intermediate images of an object at different distances with a blur effect on at least parts of the object images, and containing a set of optical elements, and having at least two pupil zones formed to provide a predetermined distribution of optical powers and aberrations within each of the at least two pupil zones, based on which point spread function is formed, defined by a curve with minimized side peaks compared to central peak in given range of object distances, each of the at least two pupil zones corresponding to a respective given range of object distances and respective given range of field angles, wherein the set of optical elements contains, arranged along the optical axis from the object side toward the image surface: a first lens, a second lens, a third lens, a fourth lens, a fifth lens and a sixth lens, where

[68] the first lens has a positive refractive power, with the surface facing the object side having a convex shape and the surface facing the image side having concave shape;

[69] the second lens has a negative refractive power, with both the surface facing the object side and the surface facing the image side having concave shape;

[70] the third lens has a positive refractive power,

[71] the fourth lens has a meniscus shape,

[72] each of the fifth and sixth lenses has a meniscus shape near the optical axis, with the surface facing the object side having a convex shape near the optical axis and the surface facing the image side having a concave shape near the optical axis;

[73] a sensor configured to simultaneously register intermediate images formed by the optical unit from different object distances and at different field angles;

[74] an image processing unit connected to the sensor and configured to process the blurred intermediate images of at least parts of the object images registered by the sensor, said images being processed based on the obtained point spread function over the given range of distances and field angles, and reconstruct resulting images without a blur effect at output regardless of object distances.

[75] Moreover, the minimized side peaks of point spread function, formed by the optical unit, do not exceed 10% of central peak over the given range of object distances.

[76] According to the invention, the given range of object distances is from 400 mm to

5000 mm, and the given range of field angles is from -40 to +40 degrees.

- [77] Furthermore, the optical unit is configured to form invariant point spread function independent of object distances over the given range, or independent of field angle, or independent of field angle and object distances.
- [78] The optical unit can be configured to form uniform curve of modulation transfer function (MTF) independent of object distances.
- [79] Moreover, in the device according to the second aspect of the invention the optical unit is further configured to simultaneously form intermediate images of an object at different distances with a blur effect on the entire image of the object.
- [80] Moreover, each optical element of the optical unit is made of an optically transparent material selected from at least one of: optical glass, optical crystal and polymer.
- [81] According to the second aspect of the invention, the device can comprise a shutter disposed in the plane of aperture diaphragm or the imaging device plane conjugate with it, and configured to control opening or closing of a given number of pupil zones.
- [82] In the device, the sensor is a matrix photodetector, or a CMOS sensor or CCD sensor, which is configured to detect electromagnetic radiation in the range of 0.4-0.7 μm , and the sensor pixel size is from 0.7 μm to 1.5 μm .
- [83] The image processing unit is configured to process intermediate images of an object and reconstruct resulting images at output based on a convolutional neural network and/or Wiener filter, parameters of which are predetermined based on parameters of the optical unit and the sensor.
- [84] Parameters of the optical unit include at least one of: radii of surfaces of the optical elements, coefficients of aspheric surfaces of the optical elements, thicknesses of the optical elements, refractive indices of materials of the optical elements, amount of dispersion of the optical elements, distances between optical elements in the optical unit, device length representing axial distance between surface of the first optical element on the object side and image surface on the sensor, and parameters of the sensor include at least one of: spectral sensitivity, noise, sampling parameters.
- [85] According to a third aspect of the invention there is provided a method for extended depth of field imaging, comprising:
- [86] simultaneously forming intermediate images of an object at different distances with a blur effect on at least parts of the object images by an optical unit having at least two pupil zones formed to provide a predetermined distribution of optical powers and aberrations within each of the at least two pupil zones, on the basis of which a point spread function is formed, defined by a curve with minimized side peaks compared to central peak over a given range of object distances, wherein each of the at least two pupil zones corresponds to a respective given range of object distances and a respective given range of field angles;

- [87] registering, by a sensor, the intermediate images simultaneously formed by the optical unit from different object distances and at different field angles;
- [88] processing, by an image processing unit, the intermediate image of the object with a blur effect on at least parts of the object images based on the obtained point spread function over the given range of object distances and field angles, and
- [89] reconstructing resulting images without a blur effect regardless of object distances.
- [90] Moreover, the minimized side peaks of the point spread function formed by the optical unit do not exceed 10% of central peak in the given range of object distances.
- [91] According to the invention, the given range of object distances is from 400 mm to 5000 mm, and the given range of field angles is from -40 to +40 degrees.
- [92] Furthermore, the optical unit is configured to form invariant point spread function independent of object distances over the given range, or independent of field angle, or independent of field angle and object distances.
- [93] The optical unit can be configured to form uniform modulation transfer function (MTF) independent of object distances.
- [94] Furthermore, in the device according to the third aspect of the invention, the optical unit is further configured to simultaneously form intermediate images of an object at different distances with a blur effect on the entire image of the object.
- [95] The image processing unit is configured to process the intermediate images of the object and reconstruct resulting images at output by the based on a convolutional neural network and/or Wiener filter, parameters of which are predetermined based on parameters of the optical unit and the sensor.
- [96] Parameters of the optical unit include at least one of: radii of surfaces of the optical elements, coefficients of aspheric surfaces of the optical elements, thicknesses of the optical elements, refractive indices of materials of the optical elements, amount of dispersion of the optical elements, distances between optical elements in the optical unit, device length representing axial distance between surface of the first optical element on the object side and image surface on the sensor, and parameters of the sensor include at least one of: spectral sensitivity, noise, sampling parameters.

Advantageous Effects of Invention

- [97] The following presents basic advantages and distinctive features of the present invention over the prior art.
- [98] Present Invention:
- [99] 1) provides a device for extended depth of field imaging (EDoF);
- [100] 2) is used in smartphone cameras and similar devices, only data from current frame is required to reconstruct image and information about device characteristics (point spread function or modulation transfer function);

- [101] 3) imaging device comprises an optical unit with a matrix sensor and an image processing unit;
- [102] 4) focal length of the imaging device is generally less than 100 mm, preferably about 3 mm in a smartphone camera;
- [103] 5) optical unit generally comprises more than two lenses and forms an intermediate blurred image on the sensor;
- [104] 6) multizone optical unit is used, with each zone working at its own depth;
- [105] 7) the invention ensures sharp image of an object, regardless of object distance, in addition, there are no boundaries between parts of the image and image resolution does not change over the field of view.

Brief Description of Drawings

- [106] The aforementioned and other features and advantages of the present invention are explained in the following description, illustrated by the drawings, in which:
- [107] Fig. 1a is a schematic view of image of a scene including a target object and background, produced by conventional methods.
- [108] Fig. 1b is a schematic enlarged view of background 'E' of image of the scene in Fig. 1a, produced by conventional methods.
- [109] Fig. 2a is a schematic view of a scene image formed by a conventional lens.
- [110] Fig. 2b is a schematic view of a scene image produced using a conventional lens with extended depth of field (EDoF).
- [111] Fig. 2c is a schematic view of a scene image after image processing process, produced by a conventional EDoF lens according to Fig. 2b.
- [112] Fig. 2d shows plots of modulation transfer function, illustrating modulation transfer coefficient (T) of image as a function of defocusing (z) value for a conventional lens and an EDoF lens.
- [113] Fig. 3a, 3b and 3c is a general diagram of present invention, where Fig. 3a shows conventionally a scene at the instant of capturing image with smartphone, Fig. 3b shows is a diagram of the invention (Key Position 1 and Key Position 2), and Fig. 3c is a scene image after processing the captured image.
- [114] Fig. 4 is a schematic view of a device for extended depth of field imaging and intermediate blurred image formed by the device and output sharp image according to the invention.
- [115] Fig. 5a, 5b and 5c shows schematically a process of forming image by a device for extended depth of field imaging without image processing according to a first embodiment of the invention, where Fig. 5a shows conventionally a scene at the instant of capturing image with a smartphone with EDoF, Fig. 5b shows a process of forming image without image processing, and Fig. 5c shows intermediate blurred image

formed.

- [116] Fig. 6a is a plot of point spread function (PSF) for a conventional autofocus device in out-of-focus position.
- [117] Fig. 6b is a plot of point spread function (PSF) for a conventional EDoF device.
- [118] Fig. 6c is a plot of point spread function (PSF) of the present device for extended depth of field imaging.
- [119] Fig. 7 shows PSF function plots for a device for extended depth of field imaging as a function of field angle (W) and object distance (d) according to an embodiment of the invention.
- [120] Fig. 8 is a schematic diagram of forming intermediate blurred image at sensor of a device for extended depth of field imaging and forming output sharp image upon reconstruction by image processing unit according to an embodiment of the invention.
- [121] Fig. 9a is a schematic diagram of forming intermediate image by a device for extended depth of field imaging, having at least two pupil zones according to an embodiment of the invention.
- [122] Fig. 9b are plots of modulation transfer function, showing modulation transfer coefficient (T) versus defocusing (z) for a device for extended depth of field imaging with two, three and multiple pupil zones according to an embodiment of the invention.
- [123] Fig. 10 is a schematic diagram of forming an intermediate image by a device for extended depth of field imaging, having at least two pupil subzones according to an embodiment of the invention.
- [124] Fig. 11a is a schematic diagram of forming two beams with respective foci $F1$, $F2$ for a device for extended depth of field imaging, having two pupil zones according to an embodiment of the invention.
- [125] Fig. 11b is enlarged view of the path of beams in the area of foci $F1$, $F2$ from the diagram of Fig. 11a, according to an embodiment of the invention.
- [126] Fig. 11c is a plot of modulation transfer function (MTF), showing modulation transfer coefficient (T) versus defocusing (z) according to an embodiment of the invention.
- [127] Fig. 12a shows a path of light beams for an imaging scheme with two foci according to an embodiment of the invention.
- [128] Fig. 12b shows a path of beams for an imaging scheme with three foci, according to an embodiment of the invention.
- [129] Fig. 12c is a plot illustrating modulation transfer function (MTF), showing modulation transfer coefficient (T) versus defocusing (z) for the imaging scheme with two foci according to Fig. 12a.
- [130] Fig. 12d is a plot illustrating modulation transfer function (MTF) showing modulation transfer coefficient (T) versus defocusing (z) for the three-focus imaging

scheme according to Fig. 12b.

- [131] Fig. 13 is a schematic view of an optical unit of a device for extended depth of field imaging with a pupil zone divided into at least two zones, where point spread function (PSF) does not depend on object distances; reference numeral 13a stands for point spread functions (PSF) for far position, central position and near position, and reference numeral 13b stands for point spread functions (PSF) as a function of field angle.
- [132] Fig. 14 is a schematic view of an optical unit of a device for extended depth of field imaging with a pupil zone divided into at least two zones, where point spread function (PSF) depends on depth of field; reference numeral 14a stands for point spread functions (PSF) as a function of depth of field for far position, central position and near position, and reference numeral 14b stands for point spread functions (PSF) as a function of field angle.
- [133] Fig. 15a is a schematic view of spots in the image plane in accordance with point spread function (PSF) for the device for extended depth of field imaging according to Fig. 13.
- [134] Fig. 15b is a schematic view of spots in the image plane in accordance point spread function (PSF) for the device for extended depth of field imaging according to Fig. 14.
- [135] Fig. 15c is a plot illustrating modulation transfer function (MTF), showing modulation transfer coefficient (T) versus defocusing (z) according to embodiments of the invention.
- [136] Fig. 16a is a schematic view of a device for extended depth of field imaging with a shutter without an image processing device.
- [137] Fig. 16b, 16c and 16d show plots illustrating modulation transfer functions (MTF) which define modulation transfer coefficient (T) versus defocusing (z) as a function of opening pupil zones, according to embodiments of the invention.
- [138] Fig. 17a, 17b, 17c and 17d show optical power distribution maps as a function of pupil zone shape.
- [139] Fig. 18 is a schematic view of a device for extended depth of field imaging, and intermediate image and output image formed by it according to the invention.
- [140] Fig. 19a and 19b show images produced by present device for extended depth of field imaging before and after processing by imaging device.
- [141] Fig. 20a is an exemplary embodiment of optical unit of a device for extended depth of field imaging according to the invention.
- [142] Fig. 20b is a plot illustrating modulation transfer function (MTF), showing modulation transfer coefficient (T) versus defocusing (z) in conventional system.
- [143] Fig. 20c is a plot illustrating modulation transfer function (MTF), showing modulation transfer coefficient (T) versus defocusing (z) in present device for

extended depth of field imaging.

- [144] Fig. 21 shows plots illustrating modulation transfer functions (MTF), showing modulation transfer coefficient (T) versus defocusing (z) for an optical unit having an aspheric surface and/or a Zernike surface according to an embodiment of present device for extended depth of field imaging.
- [145] Fig. 22a shows exemplary plots of modulation transfer function MTF for an optical unit of an imaging device according to the invention.
- [146] Fig. 22b shows exemplary plots of point spread functions (PSF) for an optical unit of the imaging device as a function of object distance (d) according to an embodiment of the invention.
- [147] Fig. 22c shows plots illustrating distortion of the optical unit of the device for extended depth of field imaging according to an embodiment of the invention.
- [148] Fig. 23a is a schematic view of an optical unit with input pupil divided into two pupil zones (PZ1, PZ2) and a sensor according to an embodiment of the device for extended depth of field imaging.
- [149] Fig. 23b shows an optical power distribution profile of the optical unit in sagittal section of the pupil according to Fig. 23a of a device for extended depth of field imaging according to the invention.
- [150] Fig. 23c shows a focal length distribution profile of the optical unit in sagittal section of the pupil according to Fig. 23a of a device for extended depth of field imaging according to the invention.
- [151] Fig. 23d is a focal length distribution map of the optical unit according to Fig. 23a of a device for extended depth of field imaging according to the invention.
- [152] Fig. 24a is a plot of point spread function (PSF) with minimized side lobes of an optical unit of a device for extended depth of field imaging according to the invention.
- [153] Fig. 24b is a plot of modulation transfer function (MTF) as a function of defocusing (depth of field), illustrating smooth curve of MTF function.
- [154] Fig. 25 illustrates a process of forming image by the optical unit and registering at the sensor, where '25a' in Fig. 25 shows conditional division of an object into parts, '25b' in Fig. 25 is a mathematical representation of the image formed by the optical unit in the form of a convolution of intensity distribution and point spread function, '25c' in Fig. 25 shows computation of point spread function for each part of the sensor, '25d' in Fig. 25 shows operations of registering image at the sensor, and '25e' in Fig. 25 shows formation of intermediate image Y_C at the sensor.
- [155] Fig. 26 is a schematic view of image of the object (Y_C) formed at the sensor (see resulting intermediate image in '25d' in Fig. 25) and reconstructed image obtained after processing in the image processing unit.
- [156] Fig. 27 is an exemplary schematic view of separable point spread function (PSF)

according to the embodiment of the invention.

- [157] Fig. 28 is an exemplary schematic view of seven-level neural network architecture according to an embodiment of the invention.

Mode for the Invention

- [158] Fig. 1a and 1b show examples of unnatural background view, where Fig. 1a on the left shows sharp image of girl's face in focus, and image of a tree in the background, where unnaturally blurred background is observed in the box. Fig. 1b is enlarged view of the background 'E' blurred image: spaces between leaves and branches of the tree, far from the camera, are shown with halos.
- [159] Conventional extended depth of field (EDoF) systems generally have expensive designs since the extended depth of field function requires additional optical elements or coating such as phase masks, phase plates, coded-aperture masks that introduce phase delay to make contrast uniform across the required image depth. Low contrast image is registered by the sensor and then image processing is fulfilled to increase contrast and improve image quality. At the same time, the provision of phase masks, for example, fourth-degree parabola mask, cubic polynomial shape mask, Toraldo mask, or coded aperture in EDoF systems, significantly increases cost or impairs their light and energy characteristics.
- [160] Fig. 2a, 2b, 2c show schematically scene images with target objects located at different distances to smartphone camera (near zone, medium zone which is focus zone, far zone) formed by conventional imaging systems.
- [161] Furthermore, Fig. 2a is a scene image captured with a conventional lens, where objects, Christmas tree and person, are blurred because they are out of focus, while car object, being in focus of smartphone camera, is sharp.
- [162] Fig. 2b is a scene image produced with a conventional extended depth of field (EDoF) lens that uses a phase mask. Here, all objects in the scene are nearly similarly blurred, including car.
- [163] Fig. 2c is a scene image after image processing provided by conventional EDoF lens according to Fig. 2b with a phase mask in the optical scheme.
- [164] Here, all objects in the scene, i.e. tree, car and person, are equally sharp.
- [165] Fig. 2d shows plots illustrating amount of modulation transfer coefficient (T) or image sharpness versus amount of defocusing (z) for a conventional lens and an EDoF lens. In Fig. 2d, the curve illustrating modulation transfer coefficient versus defocusing for a conventional lens has a sharp peak in the focus area on target object of the scene, as clearly illustrated in Fig. 2a, and the curve illustrating modulation transfer coefficient versus defocusing for an EDoF lens has a uniform, smooth character in the required range of defocusing (z), which corresponds to blurred image of all scene

objects (in Fig. 2b) within the required depth.

[166] Fig. 3a - 3c is a general view of the present invention (Fig. 3b), conventionally showing a scene at the instant of capturing image with smartphone (see Fig. 3a) and the scene image after processing the captured image (Fig. 3c).

[167] Basic solutions according to the present invention (Key Position 1 and Key Position 2).

[168] As seen in Fig. 3b, an optical imaging device has multiple pupil zones (PZ1, PZ2).

[169] Each zone is defined by own focus (F1, F2) and aberration properties.

[170] Each focus corresponds to some distance (depth) in object space. Moreover, each pupil zone corresponds to beam L1, L2, for example, zone PZ1 corresponds to light beam L1 and focus F1.

[171] Aberration properties define image quality according to image quality criteria for a range of distances.

[172] Sensor registers images from different distances simultaneously. Images at the sensor contain information on objects at different distances. Furthermore, images captured by the sensor are blurred because objects at different distances may be out of focus and overlap each other. To compensate for blurring, a function is provided for processing captured images by an image processing unit (Key Position 2), which is configured to reconstruct images at desired distance (depth) using information about optical device characteristics (modulation transfer function (MTF) or point spread function depending on distance). As a result of image processing, sharp image of objects over the entire field of the scene is displayed on smartphone screen (see Fig. 3c).

[173] Hereinafter, exemplary embodiments of the present invention will be described in detail. The exemplary embodiments are illustrated in the accompanying drawings, where the same or similar reference numerals refer to the same or similar elements or elements having the same or similar functions. The exemplary embodiments described with reference to the accompanying drawings are illustrative and used only to explain the present invention, and should not be construed in any way as imposing limitations upon the scope thereof.

[174] In the context of the present invention, the following concepts and terms shall have the following meanings assigned to them by the inventors:

[175] Target object is an object selected by user to capture.

[176] Aperture diaphragm is a diaphragm that limits the beam emerging from axial point of an object.

[177] Pupil is a paraxial image of aperture diaphragm.

[178] Pupil zone (PZ) is a selected area of pupil with own optical device properties (focal length, aberration properties).

[179] Field of view is the angle between two light beams passing through the center of the

lens entrance pupil towards displayed object points that are most distant from the optical axis in object space.

- [180] Field angle is the angle between the optical axis and the light beam passing through a point of the object in the field of view.
- [181] Spot is an image of a point, formed by real optical system.
- [182] Intermediate image is an image formed by optical unit on sensor.
- [183] Reconstructed image is an image at output of image processing unit.
- [184] Point spread function (PSF) describes distribution of illumination of a point object image as a function of coordinates in the image plane.
- [185] Bokeh effect is a blur of an out-of-focus part of image, usually background.
- [186] Halo is a light border around image of points of an object.
- [187] Modulation transfer coefficient is the ratio of contrast of image of a harmonic (sinusoidal) object to contrast of the object itself.
- [188] Modulation transfer function (MTF) shows the variation in modulation transfer coefficient (contrast) of the image as a function of spatial frequency of a harmonic object. In other words, MTF defines how accurately spatial and frequency content of the object is transferred to the image.
- [189] Defocusing is a displacement of analysis plane relative to mounting plane of the sensor.
- [190] Optical system (unit) is a set of optical elements specifically arranged in space to provide required formation of light beams (without sensor and processing unit).
- [191] According to a first embodiment, there is provided a device for extended depth of field imaging (see Fig. 4), comprising an optical unit (e.g., optical device), a sensor and an image processing unit. Fig. 5a-5c shows a schematic view of a device for extended depth of field imaging without an image processing unit. Here, the optical unit has at least two pupil zones (PZ1, PZ2) (see Fig. 3b, 4 and 5b). Furthermore, each pupil zone with respective aberration properties operates with appropriate range of object distances (d_1 , d_2 , d_3), which corresponds to its focus (F_1 , F_2 , F_3) and range of field angles (angle 1, angle 2, angle 3). Aberration properties (e.g. wavefront aberrations (OPD)) of each pupil zone determine image quality in accordance with optical unit characteristics for distance range d_1 , d_2 , d_3 , ..., d_N . The characteristics include, for example, point spread function (PSF) or modulation transfer function (MTF) for the range of object distances and field angles. The optical unit forms an intermediate blurred image, which is then corrected by the image processing unit using the optical device characteristics (PSF or MTF functions) in the range of object distances and field angles, and the image processing unit outputs a sharp contrast image of objects over the entire field of view.
- [192] Characteristics and properties of pupil zones are jointly optimized so that the optical

unit forms point spread function (PSF) with minimized side lobes (side peaks) for out-of-focus points.

- [193] Further, Fig. 6a - 6c show exemplary plots of point spread function (PSF). Fig. 6a shows a plot of point spread function (PSF) when a conventional camera optical system is defocused; as a result, images of background point objects look like ring or half-ring spots, this leading to unnatural blur of the background (donut-shaped bokeh).
- [194] Fig. 6b is a plot of defocused point spread function (PSF) for a conventional EDoF system, which shows side peaks (side lobes), as a result, images of background point objects look like spots with a ring halo, this leading to unnatural blur of the background (donut-shaped bokeh).
- [195] Fig. 6c is a plot of point spread function (PSF) of an imaging system according to the invention, where PSF function in out-of-focus position has no side lobes or has extremely minimized side lobes, this leading to uniform blurring of the background.
- [196] This effect is provided by the use of a multifocal optical unit with multiple pupil zones. As a result, the image processing unit outputs final object image with natural background blur (bokeh effect).
- [197] It should be noted that conventional EDoF systems operate in the following manner:
- [198] 1) an optical unit registers a blurred image. The image is deliberately made blurred (using amplitude-phase masks or introducing spherical aberration) to increase depth of field. In such systems, point spread function is formed with side peaks (side lobes). Side peaks give rise to a ring or semi-ring halo appearing in the point image. This is especially critical for far objects having many point sources, for example, spaces between leaves and branches of trees (see Figs. 1a and 1b). From a distance, they appear to be points, but EDoF registers them as a haloed spot due to side peaks in point spread function;
- [199] 2) the blurred image formed by the optical unit is registered by the sensor;
- [200] 3) a processing unit reconstructs sharp image from the blurred image. If the image has blurred haloed points (spots), after processing they will be converted into sharp points with sharp halo. Therefore, the image is distorted: instead of a supposed point, there is obtained a point with sharp ring.
- [201] In the optical unit of the present imaging device, blur is formed not by a phase mask or introduction of spherical aberration, but by dividing the pupil into zones with own aberration properties, although the use of a mask is not excluded. As a result, the optical unit forms a blurred image and additionally, unlike other conventional EDoFs, point spread function (PSF) has no side peaks. Point object (or point on object, point source) is converted to a blurred point (spot), but without halos.
- [202] Furthermore, the image processing unit is configured to process the intermediate blurred image (see Figs. 4 and 5b) and reconstruct the blurred image formed by the

optical unit. Image processing is performed based on distribution of PSF or MTF function over the given range of object distances and field angles. Image reconstruction is also performed based on parameters of the imaging device sensor, which include: spectral sensitivity, noise, sampling parameters, and which are used in the image reconstruction process. Thus, the processing unit reconstructs blurred image into a sharp one. Since there are no halos in the image, the blurred point image (spot) turns into a point, as it should be in naturally looking image.

- [203] Fig. 7 shows plots that illustrate examples of variation in the point spread function shape as a function of field angle and object distance. There is clearly demonstrated how the point spread function (PSF) depends on field angle (w) and object distance (d). Plots in Fig. 7 (where x is the coordinate in the image plane, I is the point spread function value) show examples of point spread function for (target) object distance of 400mm, 1000mm, 5000mm and field angles (w) of 0 degrees, 23 degrees and 40 degrees. Information obtained in experimental studies carried out by the inventors, some of which are presented in Fig. 7 as a non-limiting example, is then used in the image processing unit to reconstruct blurred image.
- [204] It should be noted that the experiments demonstrated that at each of the distances of 400 mm, 1000 m and 5000 mm to the object, the imaging device according to the invention forms point spread function with minimized side lobes, this indicating that a uniformly blurred intermediate image is formed, which in turn ensures reconstruction of sharp image after processing in the image processing unit.
- [205] In addition, the experiments showed that at field angles of -40 degrees, 0 degrees, 23 and +40 degrees and at given object distances, the imaging device according to the invention forms point spread function with minimized side lobes, this indicating the formation of uniformly blurred intermediate image, which in turn ensures reconstruction of a sharp image after processing in the image processing unit.
- [206] Based on the conducted studies, it was found that the imaging device according to the invention provides the formation of point spread function, in which the minimized side peaks (side lobes) of the point spread function formed by the optical unit do not exceed 10% of the central peak in the given range of object distances.
- [207] Fig. 8 is a schematic diagram of a process of forming a blurred image at the sensor, and the image data from the sensor is sent to the image processing unit where the image is reconstructed. Here, image processing is performed based on the point spread function (PSF) distribution, as shown in Fig. 7 over the given range of object distances and field angles. Image reconstruction is also accomplished taking into account parameters of the imaging device sensor, which include: spectral sensitivity, noise, sampling parameters, and which are used in the image reconstruction process.
- [208] It should be noted that the sensor is a matrix photodetector, in particular a CMOS

matrix photodetector or a CCD sensor, which is capable of detecting electromagnetic radiation in the range of 0.4 - 0.7 μm , and the pixel size of the sensor is 0.7 μm , 1 μm , and 1.5 μm . In another embodiment, an imaging device having at least two pupil zones is provided, as shown in Fig. 9a.

- [209] Furthermore, each pupil zone functions with respective range of object distances (d_1 , d_2 , d_N) (not shown in Fig. 9a), which corresponds to own focus (F_1 , F_2 , F_N) and the range of respective field angles. In Fig. 9a, each pupil zone corresponds to own beam, i.e. zone PZ1 corresponds to beam L1, etc., and to own spot area.
- [210] Moreover, wavefront aberrations (OPD) of each pupil zone determine image quality in accordance with point spread function (PSF) or modulation transfer function (MTF) for the range of object distances and field angles. Image processing is performed based on the dependence of PSF or MTF function on the range of object distances and field angles. Image reconstruction is also accomplished based on imaging device sensor parameters, which include: spectral sensitivity, noise, sampling parameters, and which are used in the image reconstruction process.
- [211] Fig. 9b shows plots of modulation transfer coefficient (T) versus defocusing (z) for a device with two, three, and multiple pupil zones, and corresponding number of foci. The term "multiple" in the focus context is conditional and provides for a range of foci, for example, from 3.1 mm to 2.9 mm, used in smartphone cameras.
- [212] Plot for the imaging device with multiple pupil zones, i.e. when the pupil is divided into plurality of zones, represents a smoother dependence of modulation transfer coefficient (T) on defocusing (z), in contrast to the plots when the pupil is divided into two or three zones.
- [213] Thus, an optical imaging device with more than two or three pupil zones features a smoother modulation transfer function and a greater depth of field.
- [214] According to another embodiment of the imaging device, there is provided a design in which, in addition to dividing the pupil into two zones, each zone is divided into subzones (subzone 1, subzone 2, subzone 3 and subzone N), see Fig. 10.
- [215] Each subzone has its own focus ($F_1...F_N$) and own beam L1, L2, LN. Here, section 1 is a lens section, for example, meridional, and section 2 is sagittal, or vice versa. In an ordinary axisymmetric surface (for example, spherical), these sections have the same profile. In the example shown in Fig. 10, profiles of section 1 and 2 are different, in this case asymmetric lens profile used in the imaging device according to Fig. 10 provides a greater depth of field and forms uniformly blurred intermediate image over the entire depth and field of the scene.
- [216] In this case, the optical unit generates an intermediate blurred image of the image, which is further corrected by the image processing unit based on point spread function (PSF) or modulation transfer function (MTF) for the range of object distances and field

angles. Moreover, image reconstruction is also accomplished based on parameters of the imaging device sensor, which include: spectral sensitivity, noise, sampling parameters, and which are used in the image reconstruction process.

- [217] It should be noted that depending on the number of pupil zones, each having own focal length (F_1 , F_2 , F_N), own modulation transfer function (MTF) is formed for respective beam (L_1 , L_2 , L_N).
- [218] Fig. 11a and 11b show schematic diagrams of forming two beams with respective foci F_1 , F_2 for an imaging device with two pupil zones. Fig. 11a is a schematic diagram of forming two light beams converging into foci F_1 , F_2 . Fig. 11b is an enlarged view of the path of beams near the foci F_1 , F_2 (i.e. in the area enclosed in oval in Fig. 11a).
- [219] The design with two pupil zones features a modulation transfer function (MTF) showing modulation transfer coefficient (T) versus defocusing (z) (see Fig. 11c), and having two peaks of the same height on the plot, which ensures formation of sharp image with the same modulation transfer coefficient at peak points.
- [220] Fig. 12a and 12b show beam paths for designs with two and three foci, respectively.
- [221] Fig. 12c and 12d show the respective MTF functions as a function of the amount of defocusing (z).
- [222] With the optical design with two pupil zones, the optical imaging device forms images of different contrast depending on different depths (defocusing), see Fig. 12c, which clearly illustrates the presence of at least two peaks of different height. Alternatively, Fig. 12d shows MTF function for an optical imaging device with three or more foci, provided by dividing the pupil zone into multiple zones or subzones, thereby enabling formation of images at different object distances without focusing. In this respect, as clearly illustrated in Fig. 12d, the presence of multiple peaks in the MTF plot provides a more uniform character of the MTF function.
- [223] According to one embodiment of the imaging device (see Fig. 13) with the pupil zone divided into at least two zones, an optical unit is provided, illustrating the scheme of forming beams L_1 , L_2 with the respective foci, where point spread function PSF does not depend on object distances, i.e. depth of field. Each zone (PZ_1 , PZ_2) is defined by own focus (F_1 , F_2) and aberration properties.
- [224] It should be noted that the concepts of depth of field and depth of focus both refer to the distance along the optical axis, within which the object plane and the image plane are allowed to move, respectively, provided that the image quality is still satisfactory, i.e. in our case, it can be reconstructed by the processing unit.
- [225] Moreover, each pupil zone corresponds to respective light beam L_1 , L_2 , for example, zone PZ_1 corresponds to beam L_1 and focus F_1 .
- [226] Invariance of the optical unit according to Fig. 13 is illustrated in point spread

function plots for far position, central position and near position, which have approximately the same shape of PSF function (see plots '13a' in Fig. 13) regardless of object distances, where PSF2, PSF0, PSF3 are PSF functions for far position, central position and near position, respectively.

[227] Thus, point spread functions are invariant (PSF0~PSF2~PSF3) regardless of the object distance.

[228] At the same time, as clearly seen in the plots '13b' of Fig. 13 PSF functions differ depending on the field angle. Thus, the point spread functions are different (PSF0≠PSF1) for different field angles.

[229] As seen in Fig. 15a, which shows the appearance of spots in the image plane in accordance with PSF function for the imaging device according to Fig. 13, the spots differ from each other as a function of the field angle, but are the same in depth.

[230] This capability of the optical unit of the imaging device according to the invention, i.e. independence of the produced image quality from the target object distance (depth of field) makes processing of images obtained from different distances less complicated.

[231] According to another embodiment of the imaging device (see Fig. 14) with division of pupil zone into at least two zones, an optical unit is provided that illustrates the scheme for forming beams L1, L2 with respective foci, where point spread function PSF depends on the depth of field. Each pupil zone (PZ1, PZ2) is defined by own focus (F1, F2) and aberration properties.

[232] Moreover, each pupil zone corresponds to respective beam L1, L2, for example, zone PZ1 corresponds to beam L1 and focus F1.

[233] Functionality of the optical unit shown in Fig. 14 is illustrated in point spread function plots for far position, central position and near position, which have different PSF function shape (see plots '14a' in Fig. 14) as a function of depth of field, where PSF2, PSF0, PSF3 are PSF functions for far position, central position and near position, respectively. Thus, the point spread functions are different (PSF0≠PSF2≠PSF3) for different values of depth of field.

[234] Furthermore, as clearly seen in plots '14b' of Fig. 14, illustrating the dependence of PSF function on the field angle, where PSF functions are approximately the same as a function of the field angle. Thus, point spread functions are invariant (PSF0~PSF1) for different field angles.

[235] As seen in Fig. 15b, which shows the appearance of spots in the image plane according to PSF function for the imaging device according to Fig. 14, the spots are of the same size as a function of the field angle, but differ in depth.

[236] This capability of the optical unit of the imaging device according to the invention, i.e. independence of the obtained image quality from the field of view, provides less

complicated processing of produced images.

- [237] According to another embodiment of the imaging device, the features shown in Fig. 13 and Fig. 14 can be combined in one device, i.e. invariance of point spread function is ensured simultaneously in the field of view and in depth, which makes further image processing less complicated.
- [238] According to another embodiment, an optical unit of the imaging device also provides uniform modulation transfer function (MTF), which defines the dependence of modulation transfer coefficient on defocusing (z), i.e. MTF is independent of the amount of defocusing over the desired range (uniform MTF range in Fig. 15c).
- [239] According to another embodiment, an optical unit of the imaging device unit provides both uniform modulation transfer function and invariant point spread function (see Fig. 15c).
- [240] This capability of the optical unit of the imaging device according to the invention provides less complicated processing of the produced images.
- [241] Optical unit of the imaging device comprises a set of optical elements specifically arranged in space to provide required formation of beams (without sensor and processing unit). The optical elements can be lenses having a different surface profile, and/or a composite lens, and/or a diffractive optical element, and/or a holographic optical element, and/or a polarization element, and/or an amplitude-phase mask.
- [242] Composite lens is a structure consisting of at least two zones with different optical properties. Composite lens can be a bifocal lens, a progressive lens, a Fresnel lens.
- [243] Bifocal lens is a composite lens with two zones having different focal lengths.
- [244] Progressive lens is a composite lens consisting of several zones, featuring a focal length gradient.
- [245] Fresnel lens is a composite lens consisting of several stepped regions representing respective zones of continuous profile of a conventional lens surface.
- [246] Diffractive optical element is a diffractive microstructure that performs amplitude-phase modulation of transmitted or reflected light.
- [247] Holographic optical element is a diffractive optical element manufactured by light wave interference methods.
- [248] Diffractive optical element, and in particular holographic optical element having a small thickness of $5\text{ }\mu\text{m}$, enables effective correction or introduction of chromatic aberrations.
- [249] Polarizing element is a device that changes the state of polarization. For example, a polarizer or a phase plate can be used as polarizing element. Polarizer is designed to produce polarized or partially polarized light. Phase plate introduces phase difference between orthogonal linearly polarized light components. In particular, a quarter-wave plate can be used as phase plate if the phase difference corresponds to a quarter of

wavelength, or a half-wave plate can be used as phase plate if the phase difference corresponds to half a wavelength. Phase plate can be configured to convert light from p-polarization state to s-polarization state or vice versa, convert right circular polarization to left circular polarization or vice versa, convert linearly polarized light to circularly polarized one or vice versa.

- [250] Provision of a polarizing element in the optical unit according to the invention can ensure, for example, multiple passage of light through a small number of optical elements that make up the optical unit. The multiple passage of light makes it possible to reduce the total length of the optical unit and the imaging device as a whole, thereby ensuring compactness of the device, which is key requirement for smartphones.
- [251] Furthermore, polarizing element can be used as a polarizing filter, e.g. to eliminate glare.
- [252] Amplitude-phase mask is a device that performs amplitude-phase modulation of transmitted or reflected light.
- [253] Amplitude-phase masks include, for example, masks with a fourth-degree parabola phase profile, cubic phase mask, masks with concentric annular holes in the screen and designed to provide phase delay or amplitude modulation to ensure uniform modulation transfer coefficient over the required image depth. Presence of amplitude-phase masks in the optical unit provides optimization of the point spread function (PSF) shape.
- [254] Each optical element of the set of optical elements is made of an optically transparent material selected from one of optical glasses, optical crystals and polymers.
- [255] In an embodiment of the invention, the optical unit comprises a shutter, for example, an optical shutter, preferably in the plane of aperture diaphragm or in the imaging device plane conjugate with it. Provision of an optical shutter enables adjusting the number of focal lengths of the device, i.e. control of opening or closing a definite number of pupil zones (PZ). According to Fig. 16a, three zones are provided: PZ1, PZ2 or PZ3; in this case, an intermediate image will be obtained at the sensor with the following MTF characteristics, i.e. contrast (T) versus defocusing (z) (see plots in Fig. 16b-16d).
- [256] Plot in Fig. 16b corresponds to the embodiment where all three pupil zones are open, embodiment in Fig. 16c - where one pupil zone open, and embodiment in Fig. 16d - where pupil zones PZ2 and PZ3 are open.
- [257] Optical shutter enables variation in the focal length of the device without changing position of lenses or changing focal length of individual lenses.
- [258] Presence of an optical shutter in the optical unit results in decreased area of aperture diaphragm and loss of energy (luminosity) of the optical unit, which is further compensated for by image processing in the image processing unit.

- [259] According to the invention, pupil zones are divided into zones and subzones, while the pupil zones may have different shape and different distribution of optical power within the zone.
- [260] Fig. 17a-17d show maps of optical power distribution depending on the shape of optical zones.
- [261] Fig. 17a shows a continuous multifocal asymmetric distribution of optical power, which can provide a specified distribution of point spread function (PSF) or modulation transfer function (MTF). This configuration is quite simple to manufacture.
- [262] Fig. 17b shows a continuous multifocal axisymmetric power distribution. This configuration is quite simple to manufacture.
- [263] Fig. 17c shows discrete optical power distributions (P1, P2, PN), an axisymmetric with an annular pupil shape and a planar-symmetric with a segmented pupil shape, which enable separation in depth of images formed by different zones, and this power profile simplifies the image processing process.
- [264] Fig. 17d shows a discrete multifocal (P1, P2, PN) arbitrary power distribution, which can provide a specified distribution of point spread function (PSF) or modulation transfer function (MTF).
- [265] According to one embodiment of the invention, a device and method are provided for extended depth of field imaging, based on the joint design of the optical unit and the image processing unit, where both units are computed and adjusted together taking into account features and parameters of each unit (what is referred to as end-to-end optimization).
- [266] Fig. 18 is a schematic view of an imaging device comprising, arranged in succession, an optical unit containing a set of optical elements in the form of lenses with different surface profiles through which beams L1, L2, and L3 pass, a sensor and an image processing unit.
- [267] Parameters of the optical unit include: parameters of surfaces of optical elements, for example, lens surface radii ($r_1, r_2, \dots, r_i$), parameters of optical materials, for example, optical element refractive indices $n_1, n_2, \dots, n_i$, thicknesses of optical elements and distances between them in the optical unit ($d_1, d_2, \dots, d_i$), L is the device length (axial distance between surface of the first optical element on the object side and image surface on the sensor).
- [268] Parameters of the sensor include, for example, wavelength sensitivity k_λ , noise η , and sampling parameters S.
- [269] Parameters of the image processing unit include, for example, parameters of digital filters or weights ($W_1, W_2, \dots, W_i$) of neural network layers. Based on the above parameters of the optical unit, including modulation transfer function (MTF) or point spread function (PSF) depending on target object distance and parameters of the

sensor, the image processing unit processes and then reconstructs the image.

[270] Based on the above parameters of the optical unit, sensor and image processing unit, the imaging device provides image formation and processing process such that dissimilarities between reconstructed image RI_C and initial image I_λ of the target object are minimized, for example, quadratic dissimilarity (1):

$$[271] \quad ||RI_C - I_\lambda||^2.$$

[272] Therefore, intermediate image formed at the sensor by the optical unit does not have to be of high quality and resolution, which simplifies requirements to optics, since image quality is corrected in the image processing unit.

[273] Image processing and reconstruction is performed in the image processing unit such that evaluator in the form of dissimilarity norm between reconstructed image RI_C and initial image I_λ (reference image corresponding to ideal image of the target object), norms of their visual similarity VGG (detailed description of VGG see in <https://arxiv.org/abs/1409.1556v6>) or combinations thereof, are minimized.

[274] As a non-limiting example, the processing unit may be implemented using artificial neural networks, Wiener filter, or a combination thereof.

[275] One of embodiments is based on U-net-like network widely used in image processing, disclosed in <https://arxiv.org/pdf/1505.04597.pdf>.

[276] When developing and analyzing the present invention, the inventors used seven-level embodiment of the above network architecture, see Fig. 28. In the downsize direction (for input image), the network contains blocks of several convolutions (see Fig. 28, Type1 Block - Type3 Block), while in the upsize direction (Type4 Block - Type7 Block) are used. Detailed description of the blocks can be found in <https://arxiv.org/pdf/1505.04597.pdf>.

[277] To train the network, a set of pairs of images (reference image and processed image) is used. In the training process, parameters of the blocks are determined, i.e. weights of layers $W_1, W_2, \dots, W_i$ of the neural network, predominantly using gradient optimization methods, examples of which are disclosed in <https://arxiv.org/pdf/1609.04747.pdf>.

[278] As a basic set of image pairs, high-quality images are used for reference images, and an image model on the sensor is used for processed images. Simplest model describing the optical device effect is a convolution with respective point spread function PSF with addition of parameterized noise.

[279] Accounting for noise when constructing image at the sensor makes it possible to use the network to suppress noise during image processing, which is important in view of inevitable presence of noise and its effect on the processing result.

[280] The evaluator is L1 norm (sum of modules of pixel difference between reconstructed

and reference images), or a weighted combination of L1 norm and metric of visual perception of similarity (VGG), disclosed in: <https://arxiv.org/abs/1409.1556v6>), or combinations thereof. Alternative designs based on artificial neural networks with different network architectures and evaluators can be also used. They include, for example, quadratic norm, inverse evaluator, or pyramidal loss function.

- [281] It should be noted that processing of intermediate images of the object based on a convolutional neural network, for example, U-net-like network, is performed taking into account parameters of the optical unit and the sensor. Parameters of the optical unit include at least one of: radii of surfaces of optical elements, coefficients of aspheric surfaces of optical elements, thicknesses of optical elements, refractive indices of materials of optical elements, amount of dispersion of optical elements, distances between optical elements in the optical unit, device length representing axial distance between surface of the first optical element on the object side and image surface on the sensor, while sensor parameters include at least one of: spectral sensitivity, noise, sampling parameters.
- [282] An alternative to the neural network-based design for reconstructing image formed on the sensor is the use of conventional classical algorithmic approaches.
- [283] This is, for example, a method of reconstructing a blurred image using Wiener filter (Wiener, Norbert (1949). *Extrapolation, Interpolation, and Smoothing of Stationary Time Series*. New York: Wiley. ISBN 978-0-262-73005-1.), referred to as inverse convolution with Wiener filtering.
- [284] In the context of this approach, optimal estimate of sharp image x from image y formed at sensor is obtained as a result of applying Wiener filter (X , Y are respective images in frequency domain) (2):
- [285]
$$X = \left[\frac{1H^2}{H|H|^2 + S_n/S_f} \right] Y$$
- [286] where H is the respective point spread function in frequency domain (i.e. modulation transfer function), and S_n/S_f is the inverse signal-to-noise ratio of the imaging device;
- [287] X is the image spectrum in frequency domain after processing in the image processing unit,
- [288] Y is the spectrum of intermediate image registered at the sensor.
- [289] Solutions based on Wiener filtering make it possible to implement operation of the image processing unit in real time, and thus, the solution can be used for implementing the function of preview of the reconstructed image by the user.
- [290] It should be noted that processing of intermediate images of the object based on Wiener filter is fulfilled based on parameters of the optical unit and the sensor. Pa-

rameters of optical unit include at least one of: radii of surfaces of the optical elements, coefficients of aspheric surfaces of the optical elements, thicknesses of the optical elements, refractive indices of materials of the optical elements, amount of dispersion of the optical elements, distances between the optical elements in the optical unit, device length representing axial distance between surface of the first optical element on the object side and image surface on the sensor, while parameters of sensor include at least one of: spectral sensitivity, noise, sampling parameters.

- [291] The present invention also increases image processing speed when reconstructing the image formed on the sensor, if point spread function PSF can be represented in a separable form, i.e. if given function can be broken into two one-dimensional signals: a vertical and a horizontal projection.
- [292] Fig. 27 shows an example of separable point spread function (PSF) in the form of a horizontal and a vertical profile.
- [293] Value of each pixel $x[r, c]$ in the image is equal to respective point in horizontal projection $horz[c]$ multiplied by respective point.
- [294] The use of separable point spread functions (PSFs) increases the speed of image data processing.
- [295] Fig. 19a and 19b show images produced by the inventive imaging device before and after processing by the image processing unit.
- [296] Fig. 19a shows two images of a car and a garage door in the background, at medium distance, where the first (blurred) image is input image captured by camera, and the second (sharp) image is output image, i.e. reconstructed image after processing by the image processing unit.
- [297] Fig. 19b shows two images of a balcony and house elements in the background, in far distance, where the first image is input image captured by camera, and the second (sharp) image is output image, i.e. reconstructed image after processing by the image processing unit.
- [298] Further, Fig. 20a shows an embodiment of optical unit of the imaging device, which comprises optical components arranged in succession along optical axis from the object side toward the image surface: aperture diaphragm, first lens (l₁), second lens (l₂), third lens (l₃), fourth lens (l₄), fifth lens (l₅) and sixth lens (l₆), where the first lens has a positive refractive power, with the surface facing the object side having a convex shape and the surface facing the image side having concave shape;
- [299] the second lens has a negative refractive power, with both the surface facing the object side and the surface facing the image side having concave shape;
- [300] the third lens has a positive refractive power, and
- [301] the fourth lens has a meniscus shape;
- [302] the fifth and sixth lenses both have a meniscus shape near the optical axis, with the

surface facing the object side having a convex shape near the optical axis and the surface facing the image side having a concave shape near the optical axis; and the axial distance between the object side surface of the first lens and the image surface is less than about 4.5 mm.

[303] This optical unit design, in contrast to conventional EDoF devices (US8559118) disclosed in detail in this description, makes it possible to get a large depth of field (from 200 mm to infinity), a smooth MTF function, in contrast to conventional designs having a pronounced maximum in MTF function; furthermore, in this exemplary optical unit, MTF function in the sagittal and meridional sections substantially coincides, as clearly seen in Fig. 20c.

[304] Fig. 20b is a plot illustrating MTF function defining modulation transfer coefficient (T) versus conventional defocusing (z).

[305] Fig. 20c is a plot illustrating MTF function defining modulation transfer coefficient (T) versus defocusing (z) in the present imaging device (EDoF).

[306] When developing the optical part of the imaging device, the inventors considered whether at least one of the lenses included in the optical unit may have aspheric and/or Zernike surface.

[307] Profiles of aspheric surfaces of lenses of the inventive imaging device are described by expression (3):

$$[308] \quad z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + Ar^4 + Br^6 + Cr^8 + Dr^{10} + Er^{12} + Fr^{14} + Gr^{16} + Hr^{18} + Jr^{20}$$

[309] where z - axial coordinate of a surface point relative to surface vertex, r - radial distance from optical axis, k - conical constant, c - surface curvature, A, B, S, D, E, F, G, H, J - aspheric coefficients.

[310] Moreover, for k=0, the surface has a spherical profile,

[311] k=-1< to <0, the surface has the shape of an ellipsoid with the main axis on the optical axis (oblong ellipsoid (spheroid)),

[312] k=-1, the surface has the shape of a paraboloid,

[313] k=<-1, the surface has the shape of a hyperboloid.

[314] The complex shape of lens surfaces, including aspheric ones, computed according to expression (3), provides aberration correction and enhances quality of the image produced by the device according to the invention.

[315] It should be noted that the use of aspheric surfaces provides correction of field aberrations with a small number of lenses, in this case five or six, thereby ensuring compactness of the inventive device.

[316] Furthermore, lenses with aspheric surfaces made of optical plastic according to the invention are easily molded, which reduces the cost.

- [317] To manufacture lenses with aspheric surfaces from optical glass, the aspheric surface order is chosen to be lower due to the higher refractive index of the glass and low Abbe number, which also contributes to reduction of the cost of manufacture of the device according to the invention and smartphones using the devices.
- [318] Surface profiles of Zernike lenses of the present imaging device are described by expression (4):
- [319]
$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{j=1}^{66} C_{(j+1)} ZP_j$$
- [320] where z is the coordinate of surface point along the optical axis relative to surface vertex, r is the radial distance from the optical axis, k is the conic constant, c is the vertex curvature, ZP_j is the j -th Zernike polynomial (range of j : 1 to 66), $C_{(j+1)}$ is the coefficient for ZP_j .
- [321] Lens surfaces manufactured according to expression (4), i.e. Zernike surfaces, provide correction of aberrations and enhance quality of the image produced by the device according to the invention.
- [322] It should be noted that the use of Zernike surfaces provides correction of field aberrations with a small number of lenses, in this case five or six, ensuring compact device according to the invention.
- [323] At the same time, these lenses are difficult to manufacture, but the contribution to the quality of the image produced is very high.
- [324] Fig. 21 shows plots illustrating MTF function defining modulation transfer coefficient (T) versus defocusing (z) for an optical unit having an aspheric surface and/or a Zernike surface according to an embodiment of the present imaging device (EDoF).
- [325] As can be seen from the plots, the use of Zernike surface provides a more uniform modulation transfer function in the range of object distances from 200 mm to 5000 mm (corresponding depth of field from about -0.03 mm to 0.03 mm) compared to aspheric surface.
- [326] Fig. 22a shows exemplary plots of modulation transfer function MTF for the inventive optical unit, defining modulation transfer coefficient (T) versus defocusing (z) at frequency of 100 lines/mm for points with coordinates of 0, 1.9 and 2.5 mm. Solid line stands for the meridional section, and dotted line for the sagittal section.
- [327] Fig. 22b shows respective point spread function plots for a point on the axis at the (target) object distance d equal to 200mm, 400mm, 5000mm. On the plots, x is the coordinate in the image plane, I is the point spread function value. It should be noted that there is substantially no side peaks for far object ($d=5000\text{mm}$), which provides a naturally looking bokeh effect (without images of ring and oval-shaped point objects).
- [328] Fig. 22c shows exemplary plots illustrating optical unit distortion according to an

embodiment of the present imaging device (EDoF).

[329] The abscissa shows the distortion value in percent, and the ordinate shows the image size in mm. In one embodiment, the maximum image size of 2.78 mm corresponds to the field angle of 40 degrees (field of view of 80 degrees). In this case, the distortion does not exceed 2% for the optical unit.

[330] Preferred embodiment of the present imaging device (see Fig. 18) is defined by point spread function (PSF) in out-of-focus position with minimal side lobes, which is shown in the plot of Fig. 24a. The plot clearly illustrates maximum value P of side lobe peaks (level of side lobes or value of side peaks) which is less than $0.1 \cdot A$, where A is the maximum value of PSF function (or central peak), i.e. $P \leq 0.1 \cdot A$, resulting in the absence of ring or semi-ring halos on the image of object points.

[331] This effect is achieved through the use of a multifocal optical unit with multiple pupil zones. As a result, naturally looking bokeh effect is obtained in intermediate blurred image of the object at output of the optical image processing unit.

[332] Preferred embodiment of the present imaging device (see Fig. 18) is also defined by modulation transfer function (MTF).

[333] Fig. 24b is a plot of MTF function versus defocusing (depth of field) illustrating smooth MTF curve. Here, nonuniformity U of MTF function, depending on focal lengths in a given range of depth of field determined by focal lengths, is less than 20% in the range of frequencies $0.5N - 0.9N$, where N is the Nyquist frequency.

[334] In this case, nonuniformity U is determined according to expression (5) :

[335]
$$U = (\max - \min) / (\max + \min) \cdot 100\%,$$

[336] where max is maximum value of MTF function in given range,

[337] min is minimum value of MTF function in given range.

[338] In these conditions, the range of focal depth is from -0.03 mm to 0.03 mm, and respective depth of field is from 200 mm to 5000 mm.

[339] The plots presented in Fig. 24a, 24b, were obtained based on data from experiments carried out by the inventors when preparing the invention.

[340] Therefore, the inventors have developed a method and device for extended depth of field imaging, which offer the following advantages:

[341] - no movement of optical elements is required,

[342] - no complex optics (additional optical elements) are required,

[343] - optical unit with extended depth of field without autofocus is provided,

[344] - no focusing delay,

[345] - fast reconstruction algorithm,

[346] - no need for user interaction,

[347] - no control over the process of capturing image by the smartphone user is required (i.e. the user does not need to select the focus area),

- [348] - the object is always in focus, regardless of the distance to camera,
- [349] - a simple image data processing algorithm,
- [350] - inexpensive, compact imaging device applicable for mass production.
- [351] Fig. 23a is a schematic view of an optical unit with the entrance pupil divided into two pupil zones (PZ1, PZ2) and a sensor according to an embodiment of the imaging device. Beams enter the optical unit, conventionally shown as a single lens, through the entrance pupil located in the object space and divided into two zones. Two parallel beams (the number of beams matches the number of pupil zones, and their number is not limited to the example shown in Fig. 23a) pass through the optical unit in the form of a set of lenses (Fig. 23a conventionally shows a single lens). The point of intersection of rays in the beam sets focal length EFL (EFL1 for the first beam L1 and EFL2 for the second beam L2), measured from principal plane of the optical unit to the point of intersection of rays in the beam along the optical axis. Variation in the optical power P or the focal length EFL as a function of pupil coordinates (x, y) specifies an optical power distribution map or a focal length distribution map, respectively, as shown in Fig. 23b and 23d. The sensor is disposed at distance z' from the optical unit and configured to capture images formed by the optical unit through pupil zones (PZ1, PZ2). In this case, different focal lengths correspond to different distances z in the object space, where $z = z' / \text{EFL}^2$. Thus, the sensor contains information about target objects at different distances, but the image formed at the sensor is blurred, as already detailed in the description. "Blur" level of the image is described by point spread function (PSF).
- [352] Fig. 23b, 23c, 23d show optical power distribution maps of the optical unit according to Fig. 23 of the imaging device according to the invention. Optical power distribution map (P) can be represented as a function of pupil coordinates from focal length (EFL) or $P = 1/\text{EFL}$, as can be clearly seen in plots of Fig. 23b, Fig. 23c. Fig. 23d shows a map of focal length distribution as a function of pupil coordinates. Fig. 23c shows focal length distribution in the sagittal section of the pupil (i.e. this is profile of focal length distribution on the map from Fig. 23d with zero y coordinate on the pupil).
- [353] Level of blur can be described by point spread function PSF (x, y) , where x, y are coordinates on the sensor. Point spread function depends on object distance and field angle at which the object is observed. PSF (x, y) function is defined by form of pupil and aberration properties (for example, wave aberrations (OPD)). Wave aberrations (OPD) of each pupil zone define or specify image quality in accordance with the optical device characteristics for distance range $d_1, d_2, d_3, \dots, d_N$. PSF function describes the response of the optical unit to a point object. The book: Goodman J.W. "Introduction to Fourier Optics" second edition, New York: McGraw - Hill, 1996, p.145, describes in details how point spread function (PSF) can be obtained.

[354] Intensity distribution or intensity of image I_C as a function of coordinates in the image (hereinafter referred to as image I_C), formed by the optical unit on at least a part of the sensor, within which the point spread function can be considered invariant (i.e. point spread function does not depend on field angle) can be represented as a convolution of object intensity distribution I_λ (or object intensity reduced to the sensor, which matches ideal image of the object) and function PSF: $I_C = I_\lambda * (PSF)_\lambda(x, y)$. It should be noted that λ in subscript means wavelength dependence. Considering wavelength sensitivity of the sensor k_λ , i.e. spectral sensitivity, formed image

[355]
$$I_C = \int I_\lambda * (PSF)_\lambda(x, y) k_\lambda d\lambda$$

[356] where I_C is image intensity (hereinafter referred to as image) formed on at least part of sensor, I_λ is object intensity depending on wavelength (λ) formed on at least part of the sensor, $(PSF)_\lambda(x, y)$ is point spread function depending on the wavelength (λ), k_λ is sensitivity of the sensor to wavelength (λ), and $d\lambda$ is radiation wavelength differential.

[357] Image I_C formed at the sensor is digitized, i.e. becomes discrete with sensor pixel repetition rate, sampled by level (256 sampling levels in the best mode), integrated over sensor pixels and becomes noisy η , yielding resulting (intermediate) image: $Y_C = S(I_C) + \eta$, where S is sampling operator, η - noise, I_C - intensity of the image formed on at least part of the sensor. Resulting image is sent to image processing unit.

[358] '25a' in Fig. 25 is a schematic view of an imaging process taking place in the optical unit and at the sensor. '25c' in Fig. 25, the object under consideration is conditionally divided into parts, within which point spread function can be considered invariant, i.e. PSF function is treated as invariant. Optical unit of the imaging device can be mathematically represented as a convolution of intensity distribution on the object and point spread function ('25b' in Fig. 25). PSF function is computed for each sensor part (see '25c' in Fig. 25). Sensor is defined by spectral sensitivity k_λ and introduces (adds) noise (η) to the intermediate image ('25d' in Fig. 25). The image formed at the sensor is digitized (S). '25e' in Fig. 25 shows formation of resulting intermediate image at the sensor.

[359]
$$Y_C = S(I_C) + \eta, I_C = \int I_\lambda * (PSF)_\lambda(x, y) k_\lambda d\lambda$$

[360] Fig. 26 is a schematic view of object image (Y_C) formed at the sensor (see resulting intermediate image in '25d' in Fig. 25 and reconstructed image produced after processing in the image processing unit). Thus, using information about registered image by sensor (Y_C) and the dependence of point spread function from coordinates on the sensor PSF (x, y), image processing unit is capable of processing images such

that dissimilarity between reconstructed image RI_C and ideal image I_λ of the object is minimized, for example: $\min ||RI_C - I_\lambda||^2$.

Industrial Applicability

- [361] Device and method for extended depth of field imaging can be used in compact, portable devices, such as tablet computers, laptops, teleconferencing systems, in addition, it can be used for capturing photo and video with EDoF cameras of smartphones running Android, iOS, HarmonyOS and similar operating systems, and in other devices which need to capture objects at different distances in real time. Furthermore, the invention can be used in security devices, CCTV cameras, devices for taking biometric data, in microscopy, in security systems for iris recognition on the move with instant object fixation without focusing and contactless fingerprinting.

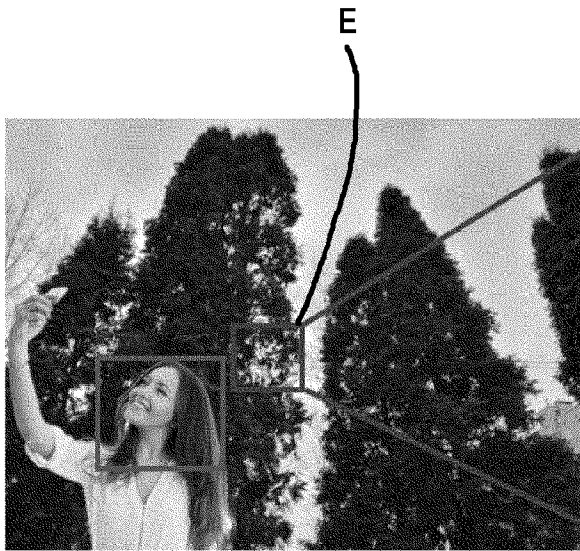
Claims

- [Claim 1] A device for extended depth of field imaging, comprising:
an optical unit configured to simultaneously form intermediate images of an object at different distances with a blur effect on at least parts of the object images, and containing at least one optical element, and having at least two pupil zones formed to provide a predetermined distribution of optical powers and aberrations within each of the at least two pupil zones, based on which point spread function is formed, defined by a curve with minimized side peaks compared to central peak in given range of object distances, each of the at least two pupil zones corresponding to a respective given range of object distances and respective given range of field angles;
a sensor configured to simultaneously register intermediate images formed by the optical unit from different object distances and at different field angles;
an image processing unit connected to the sensor and configured to process the blurred intermediate images of at least parts of the object images registered by the sensor, said images being processed based on the obtained point spread function over the given range of distances and field angles, and reconstruct resulting images without a blur effect at output regardless of object distances.
- [Claim 2] The device of claim 1, wherein the minimized side peaks of the point spread function, formed by the optical unit, do not exceed 10% of the central peak in the given range of object distances.
- [Claim 3] The device of claim 1 or 2, wherein the given range of object distances is from 400 mm to 5000 mm.
- [Claim 4] The device of claim 2, wherein the given range of field angles is from -40 to +40 degrees.
- [Claim 5] The device of any one of claims 1 to 4, wherein the optical unit is configured to form invariant point spread function independent of object distance over the given range.
- [Claim 6] The device of any one of claims 1 to 4, wherein the optical unit is configured to form invariant point spread function independent of field angle.
- [Claim 7] The device of any one of claims 1 to 4, wherein the optical unit is configured to form invariant point spread function independent of field angle and object distance.

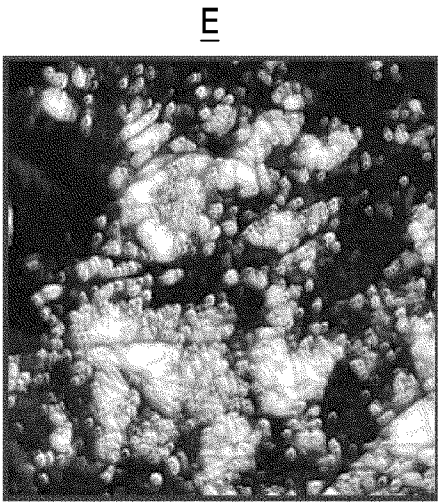
- [Claim 8] The device of any one of claims 1 to 4, wherein the optical unit is configured to form uniform modulation transfer function (MTF) independent of object distance.
- [Claim 9] The device of any one of preceding claims, wherein the optical unit is further configured to simultaneously form intermediate images of the object at different distances with a blur effect on the entire image of the object.
- [Claim 10] The device of claim 1, wherein the optical unit comprises at least one optical element, which is at least one of: lens with different surface profiles, composite lens, diffractive optical element, holographic optical element, polarizing element, amplitude-phase mask.
- [Claim 11] The device of claim 10, wherein optical elements of the optical unit comprise, arranged along the optical axis from the object side toward the image surface, a first lens, a second lens, a third lens, a fourth lens, a fifth lens and a sixth lens, where
the first lens has a positive refractive power, with the surface facing the object side having a convex shape and the surface facing the image side having concave shape;
the second lens has a negative refractive power and with both the surface facing the object side and the surface facing the image side having concave shape;
the third lens has a positive refractive power,
the fourth lens has a meniscus shape,
each of the fifth and sixth lenses has a meniscus shape near the optical axis, with the surface facing the object side having a convex shape near the optical axis and the surface facing the image side having a concave shape near the optical axis.
- [Claim 12] The device of claim 1, further comprising a shutter disposed in the plane of aperture diaphragm or the imaging device plane conjugate with it,
wherein the shutter is configured to control opening or closing of given number of pupil zones.
- [Claim 13] The device of claim 1, wherein the sensor is a matrix photodetector.
- [Claim 14] The device of claim 13, wherein the matrix photodetector is configured to detect electromagnetic radiation in the range of 0.4 - 0.7 μm , and the sensor pixel size is from 0.7 μm to 1.5 μm .
- [Claim 15] The device of claim 1, wherein the image processing unit is configured to process intermediate images of the object and reconstruct resulting

images at output based on a convolutional neural network and/or Wiener filter, parameters of which are predetermined based on design parameters of the optical unit and the sensor.

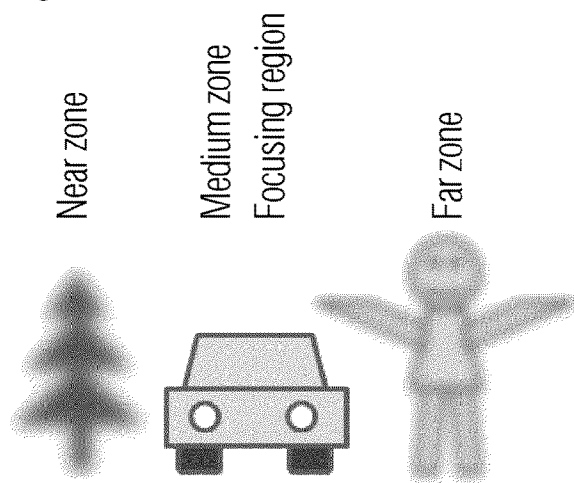
[Fig. 1a]



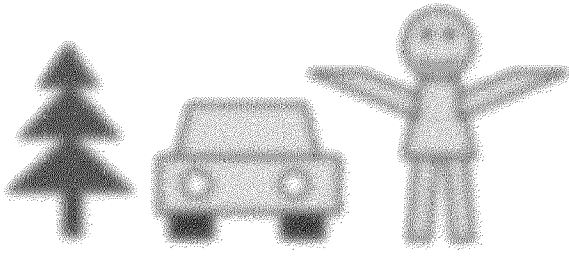
[Fig. 1b]



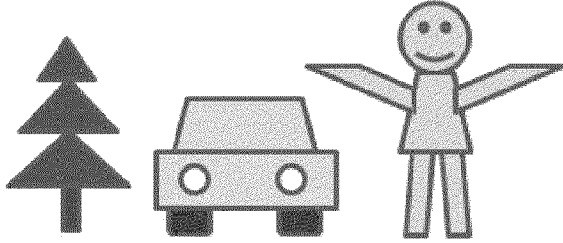
[Fig. 2a]



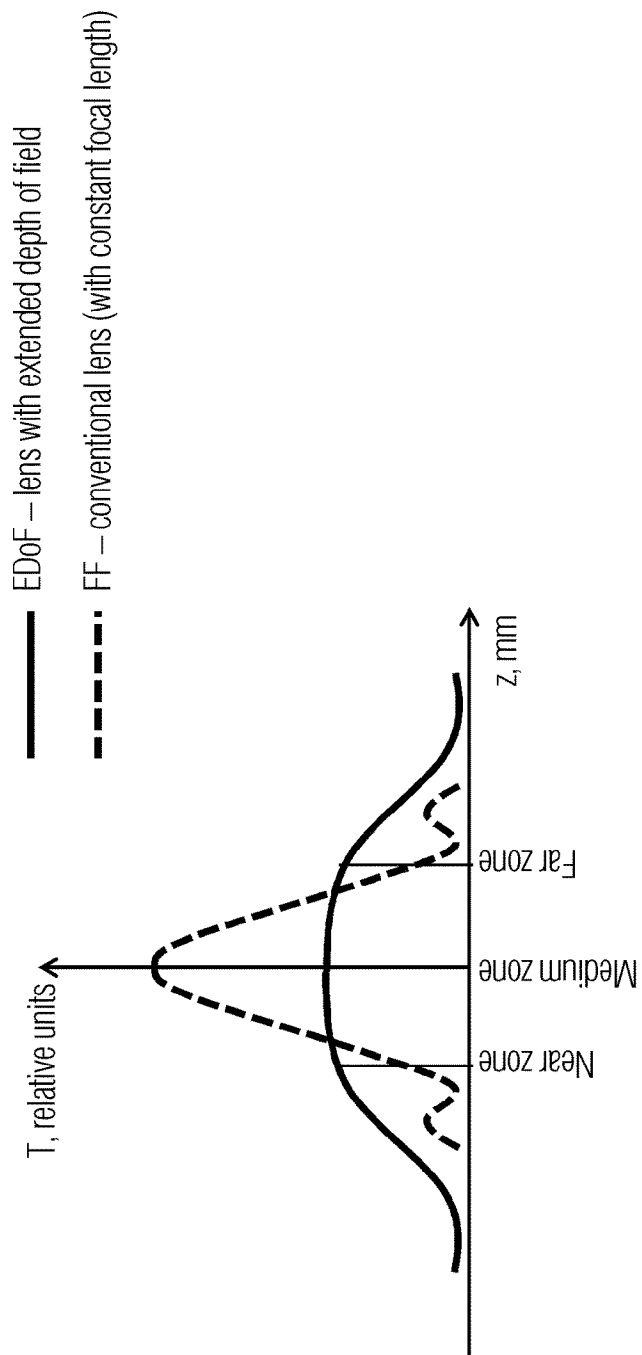
[Fig. 2b]



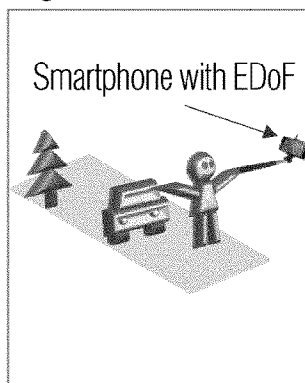
[Fig. 2c]



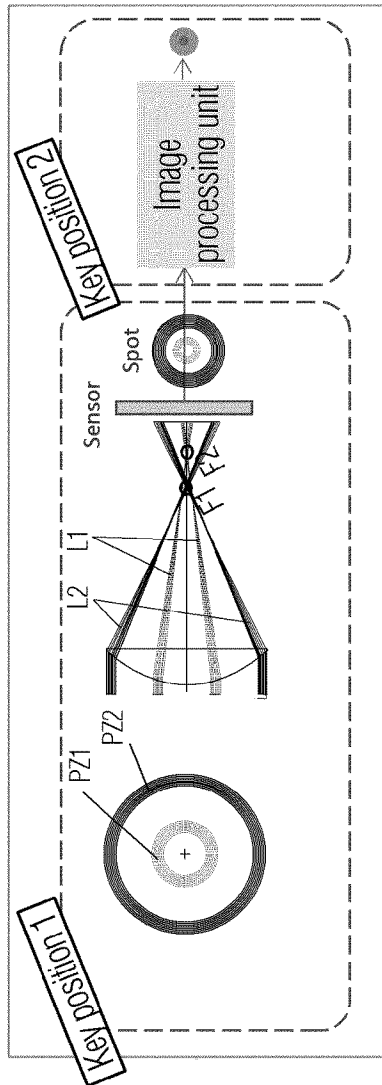
[Fig. 2d]



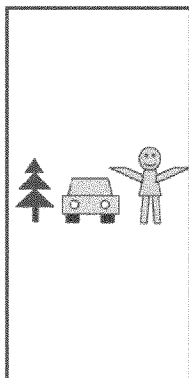
[Fig. 3a]



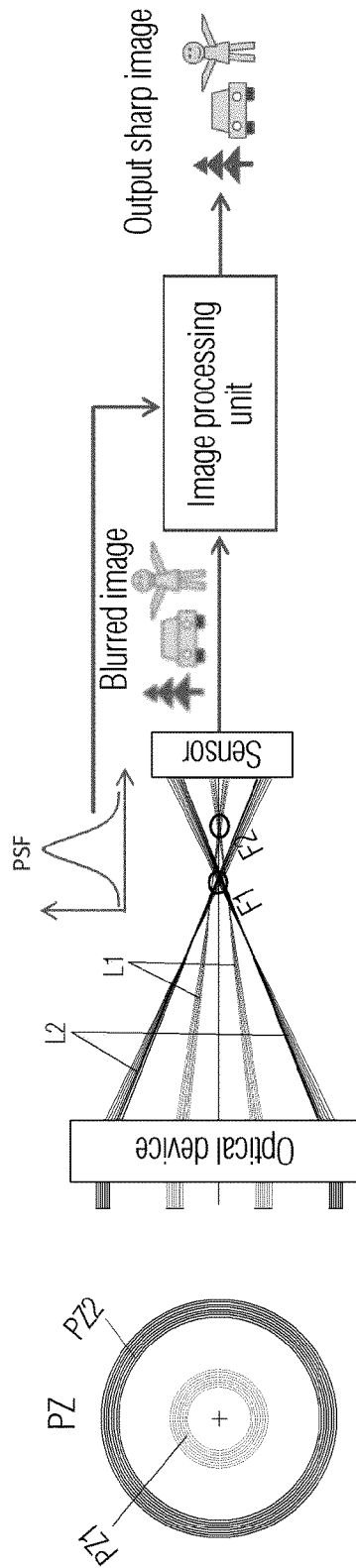
[Fig. 3b]



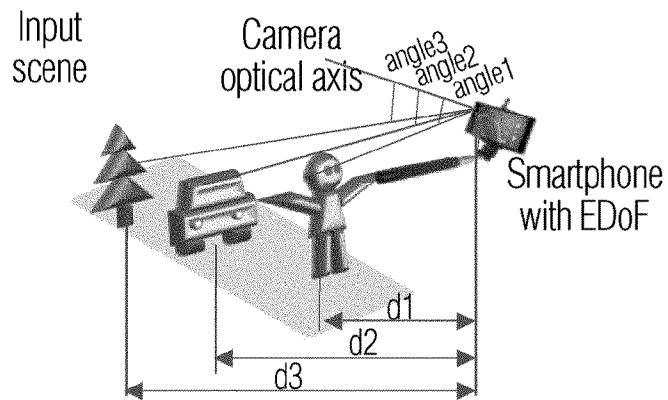
[Fig. 3c]



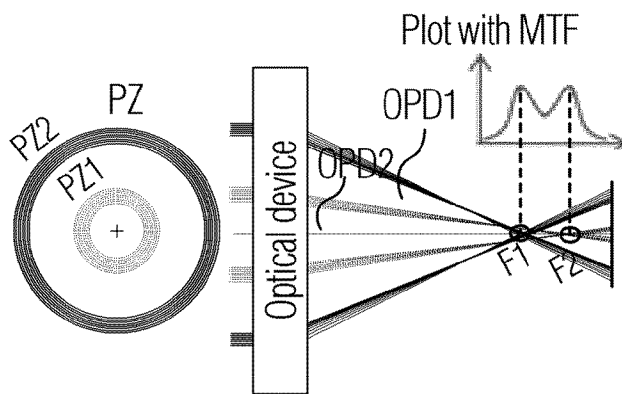
[Fig. 4]



[Fig. 5a]



[Fig. 5b]



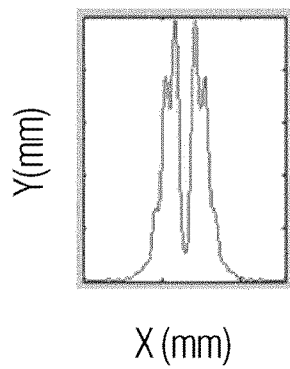
[Fig. 5c]

Intermediate blurred image



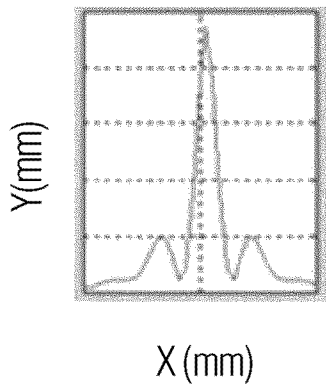
[Fig. 6a]

PSF for conventional AF system



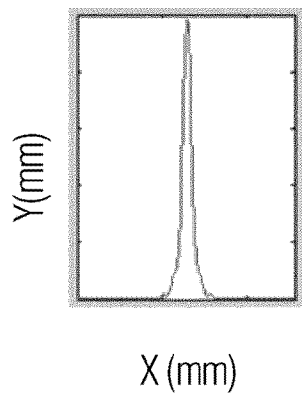
[Fig. 6b]

PSF for conventional EDoF system

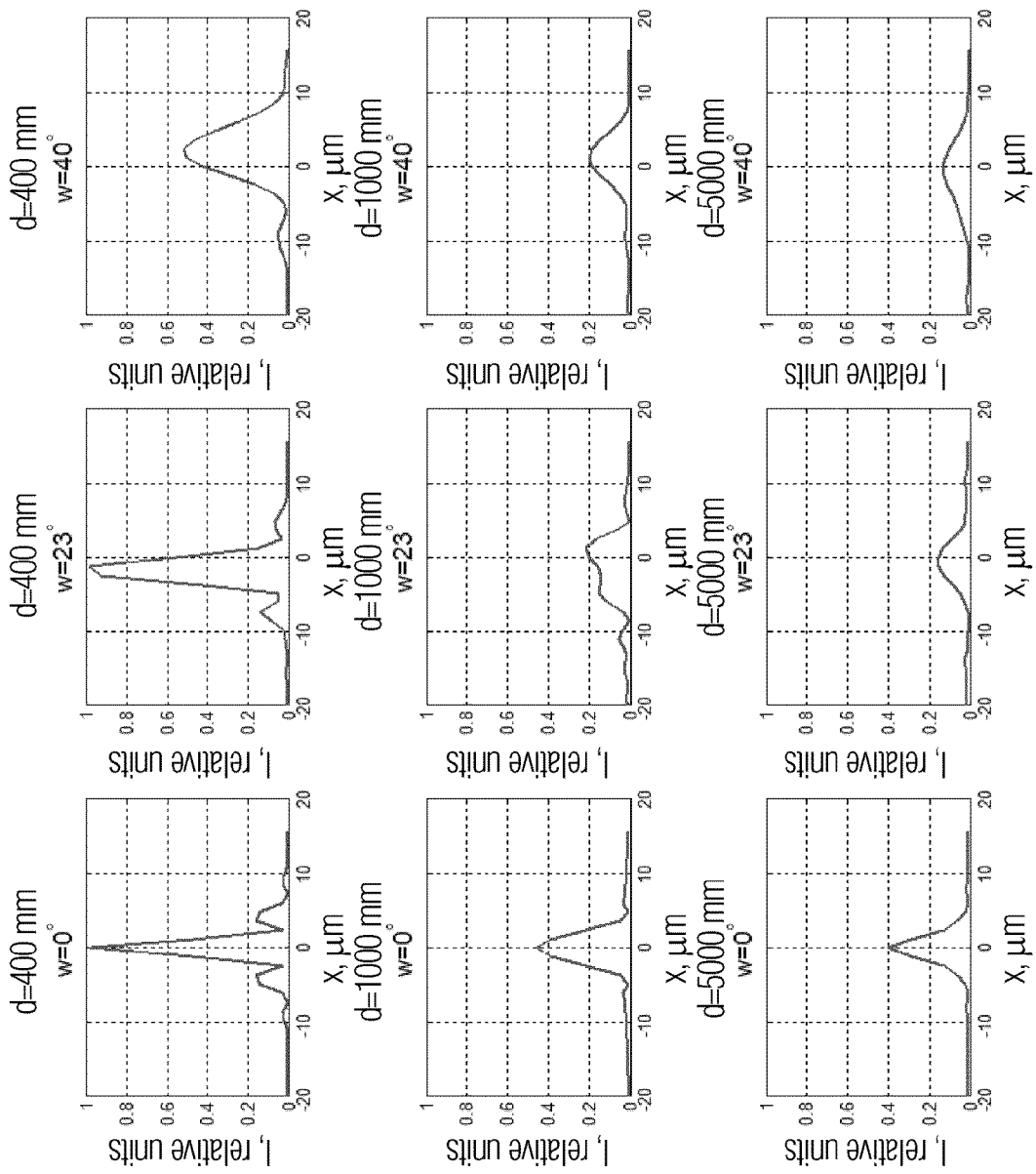


[Fig. 6c]

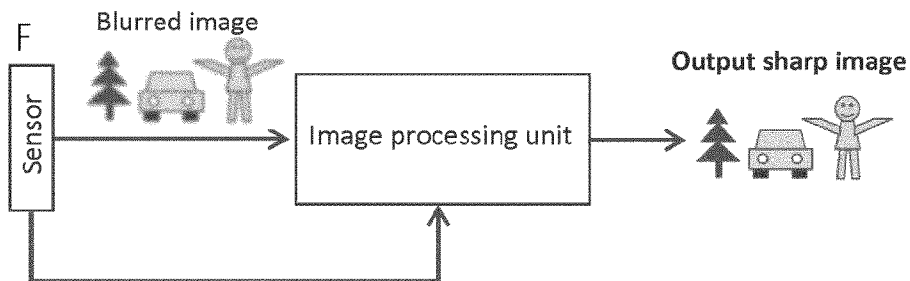
PSF for present AF system



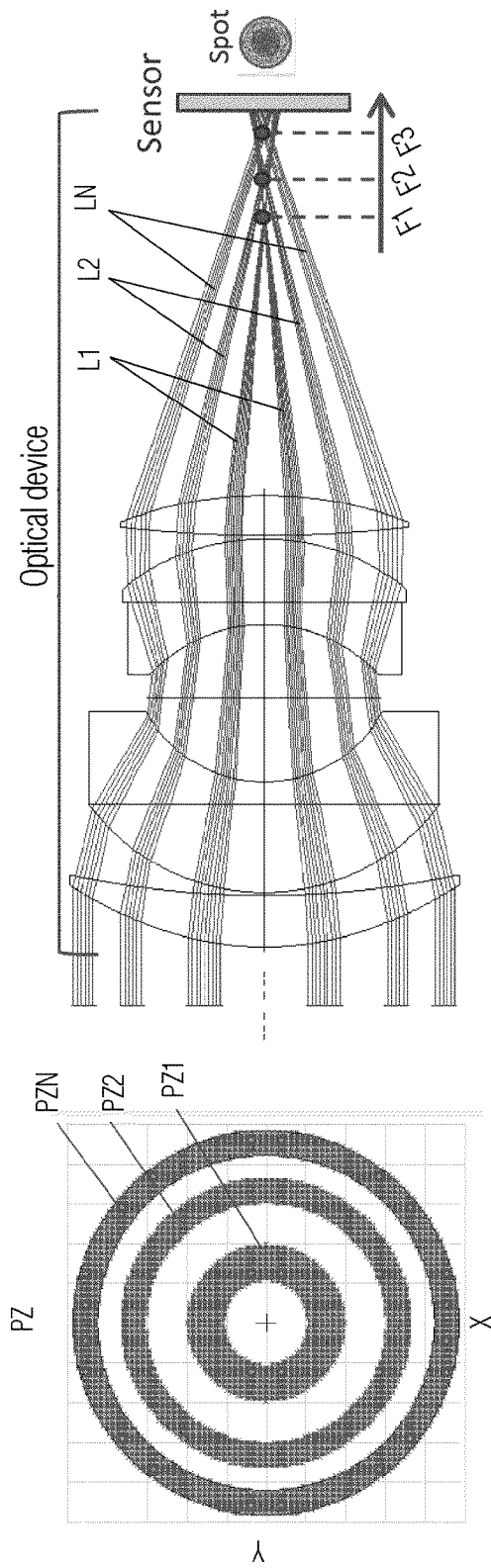
[Fig. 7]



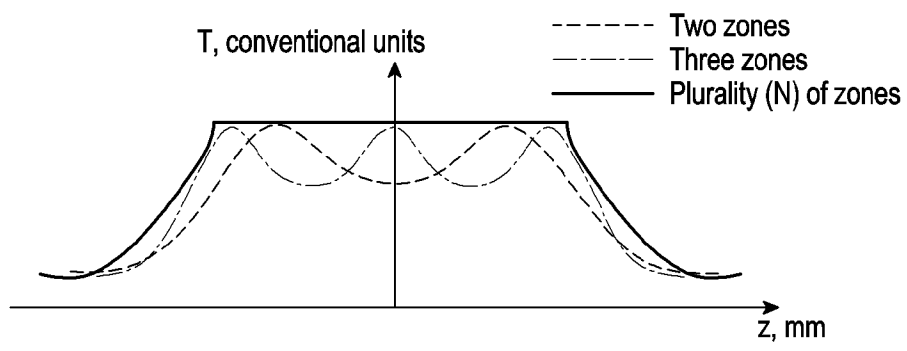
[Fig. 8]



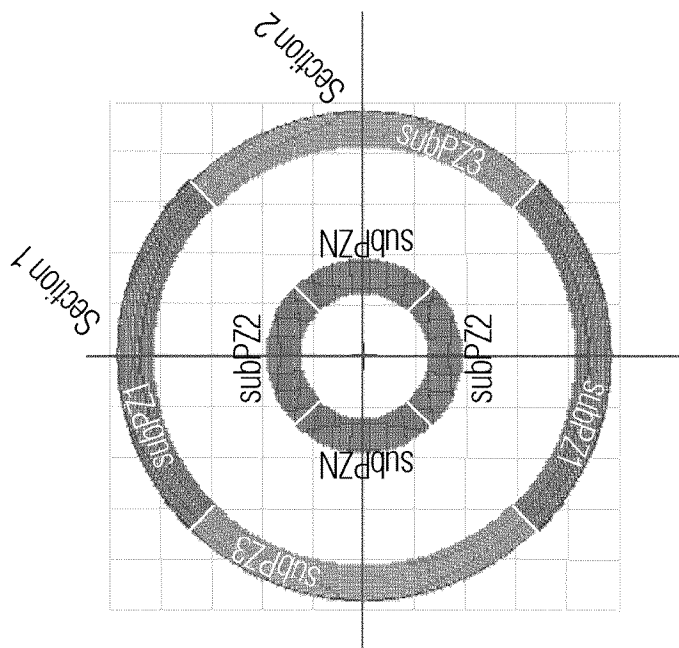
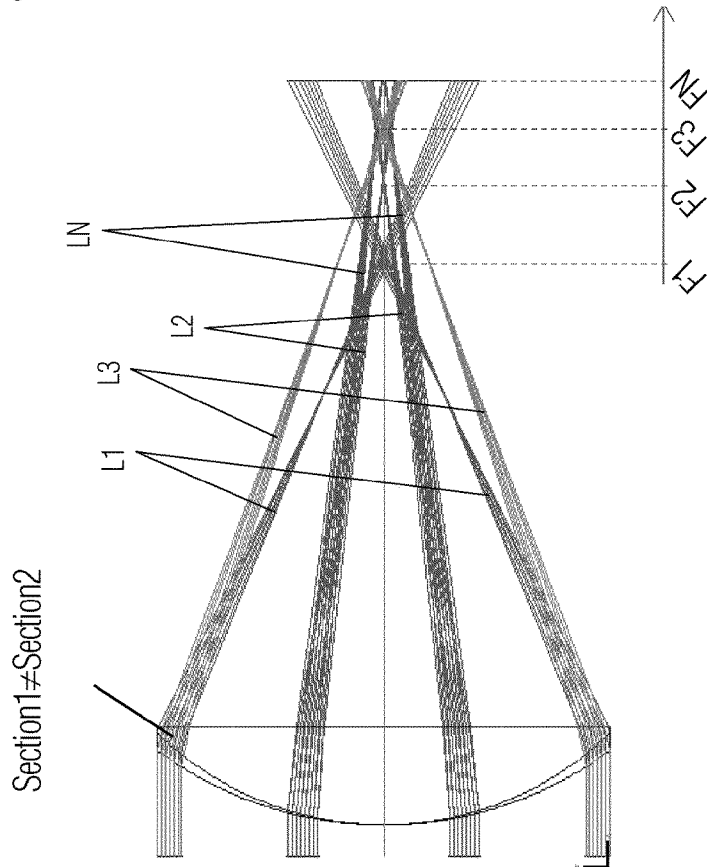
[Fig. 9a]



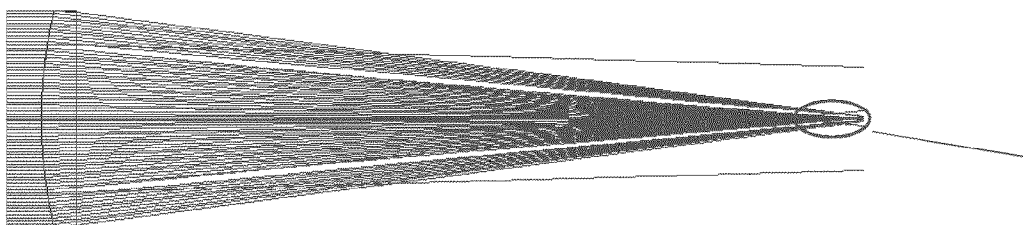
[Fig. 9b]



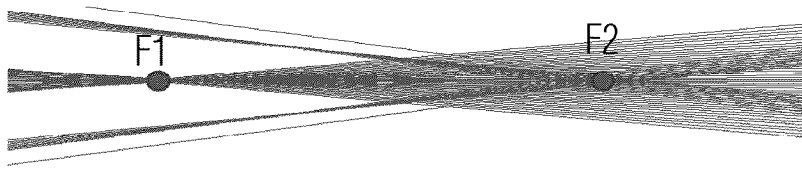
[Fig. 10]



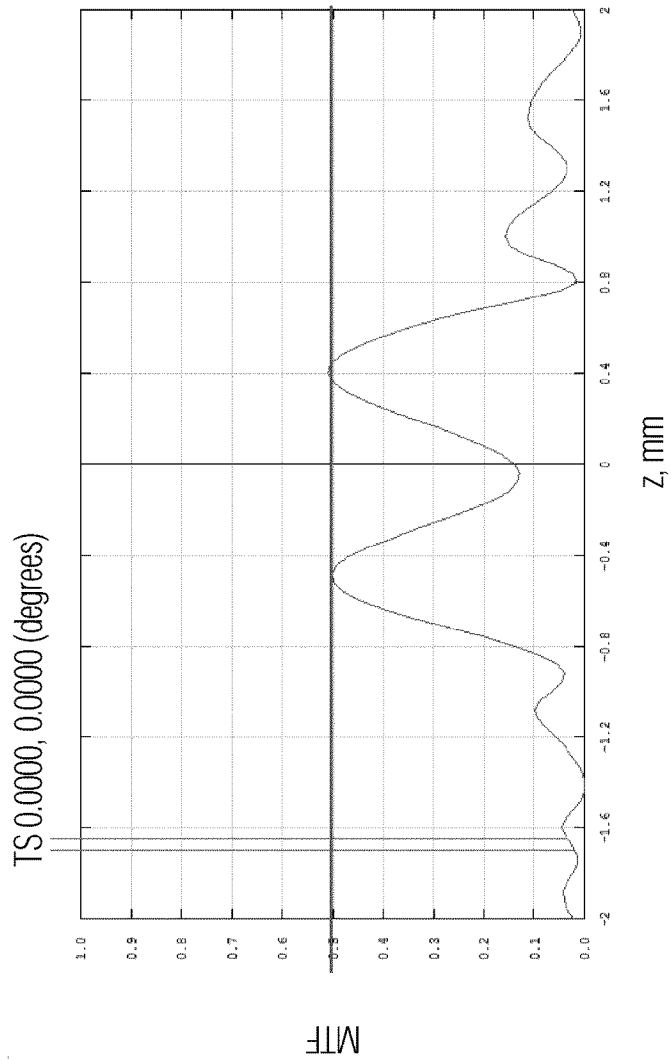
[Fig. 11a]



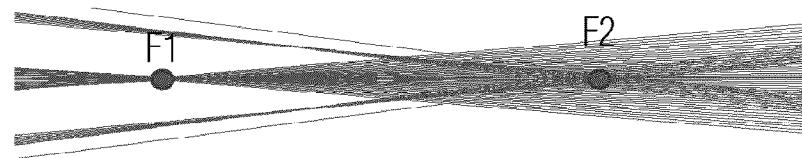
[Fig. 11b]



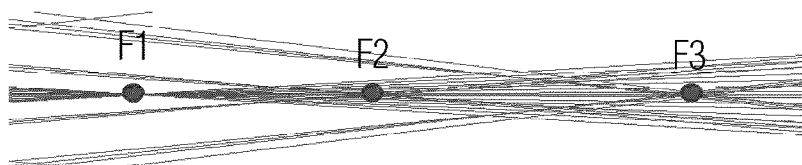
[Fig. 11c]



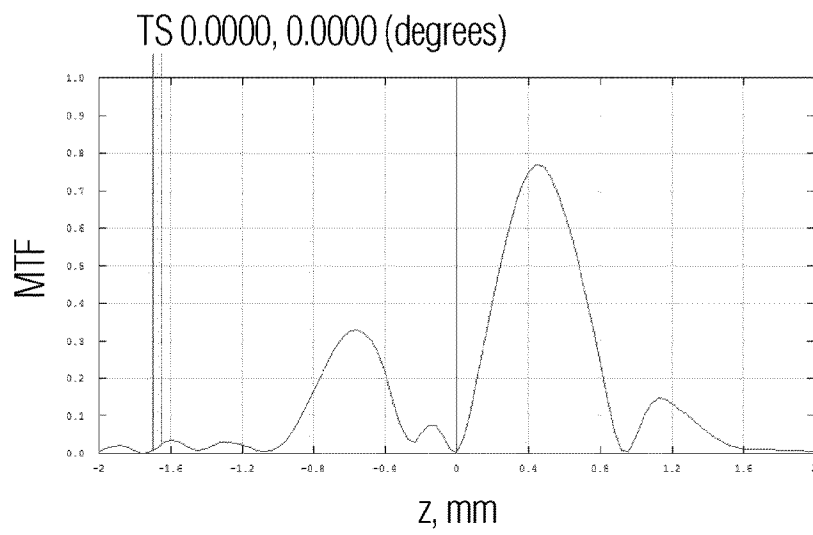
[Fig. 12a]



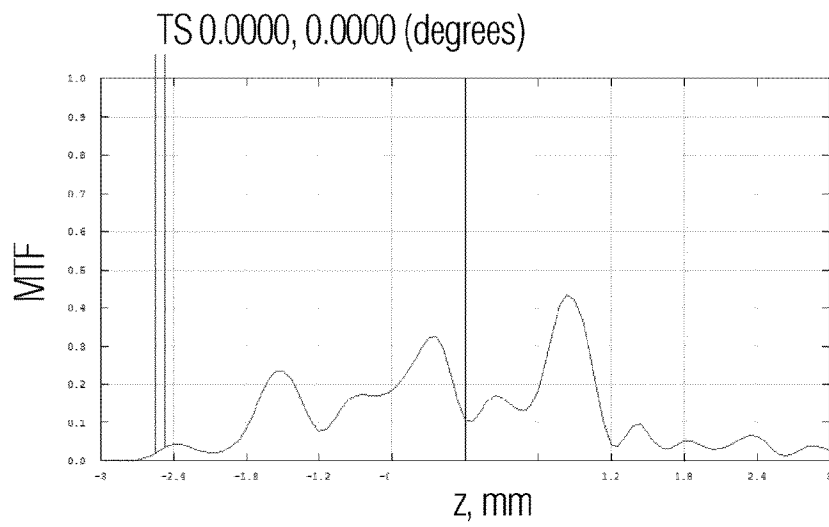
[Fig. 12b]



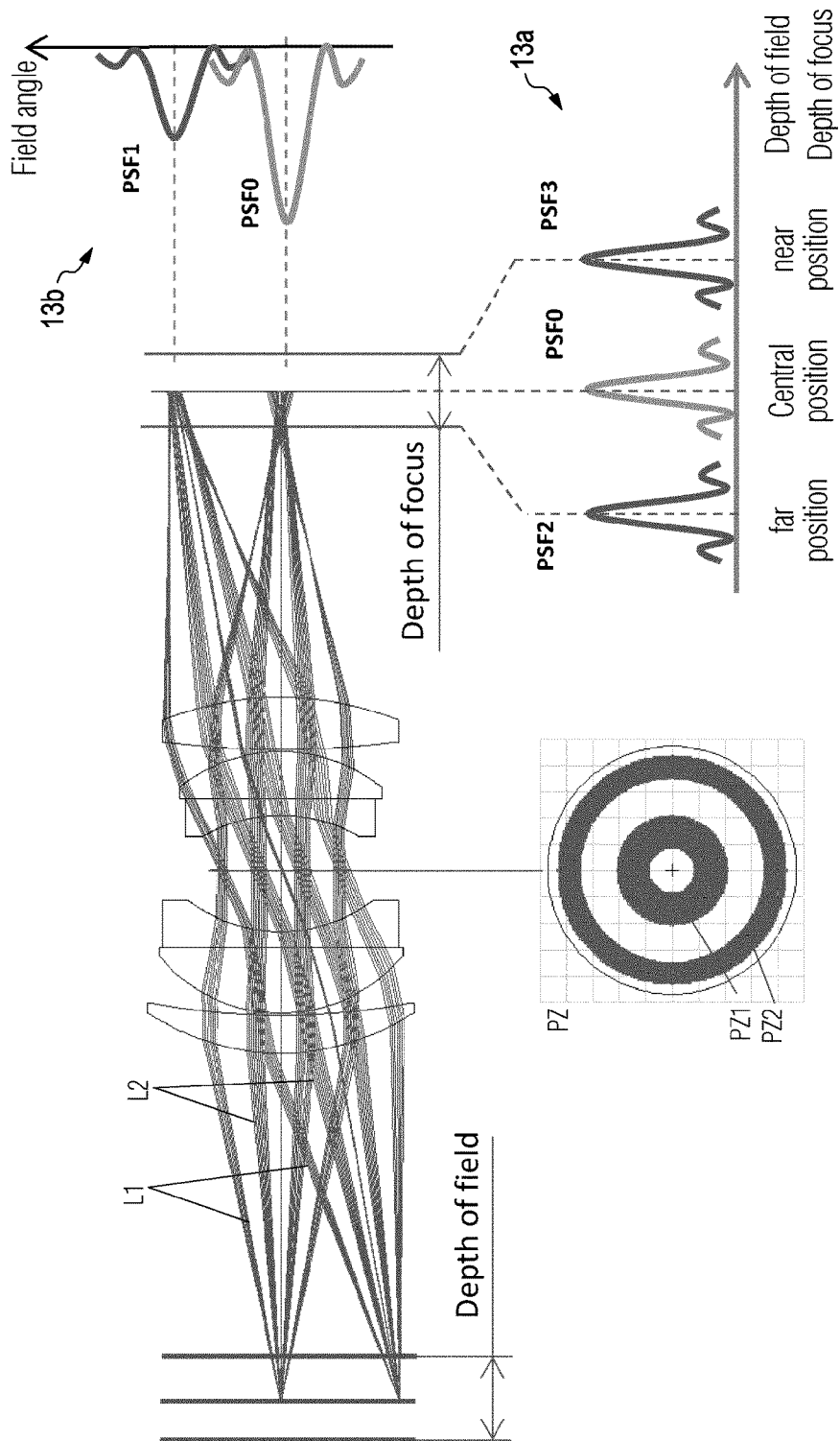
[Fig. 12c]



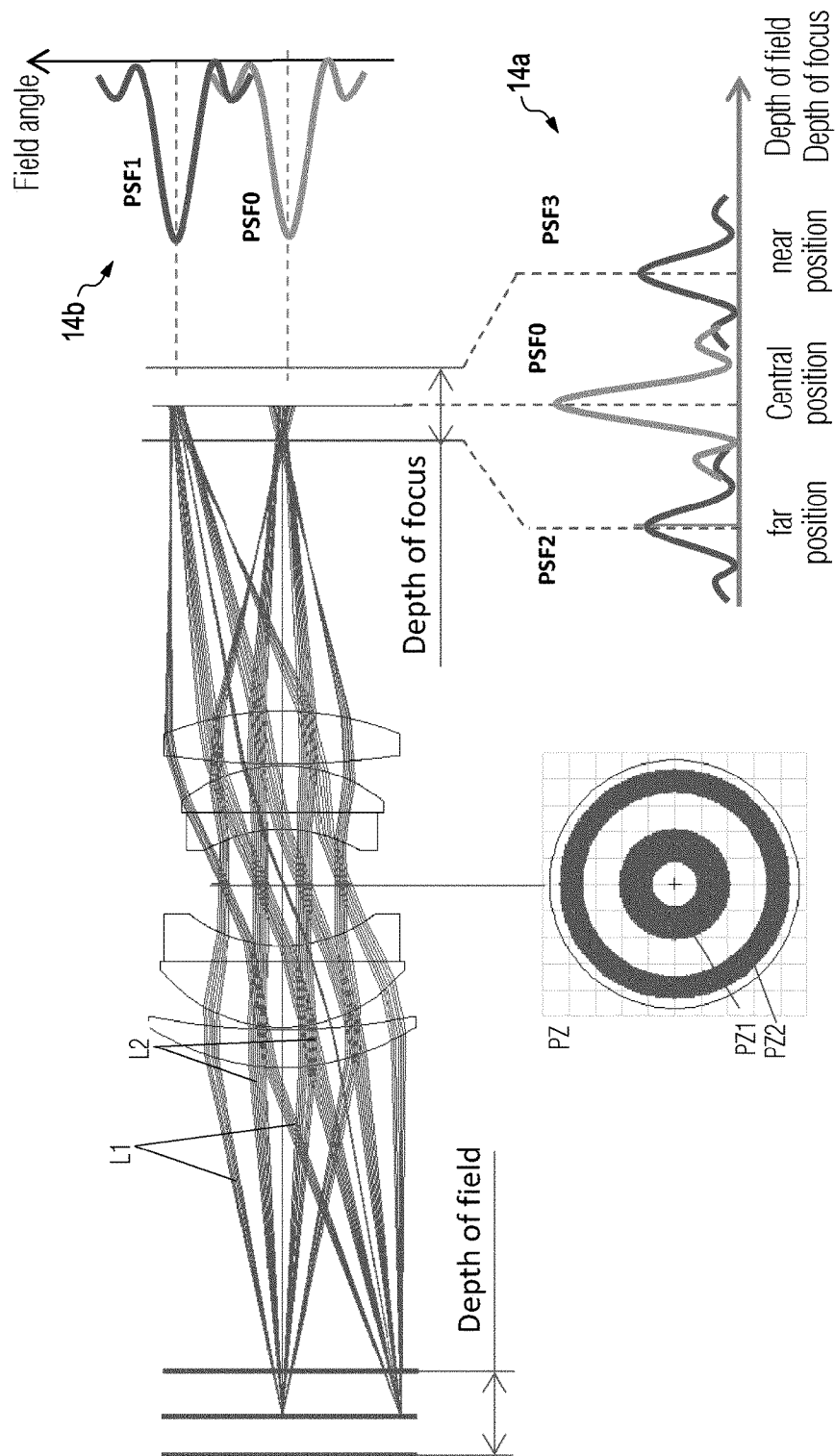
[Fig. 12d]



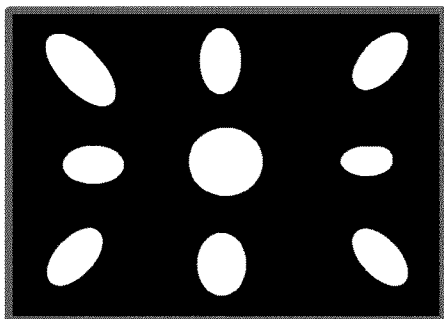
[Fig. 13]



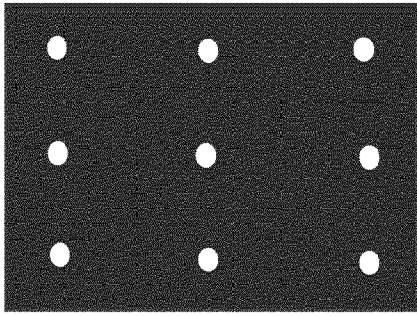
[Fig. 14]



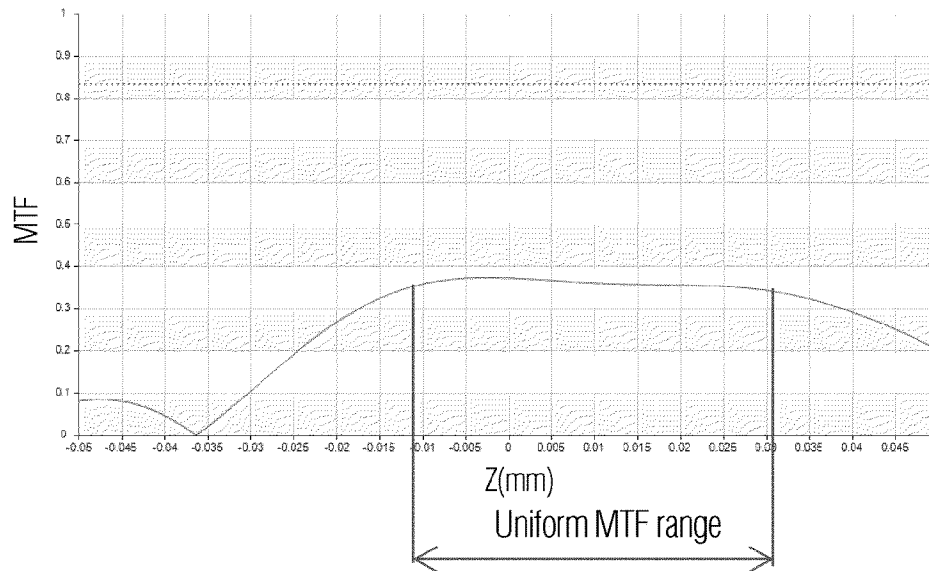
[Fig. 15a]



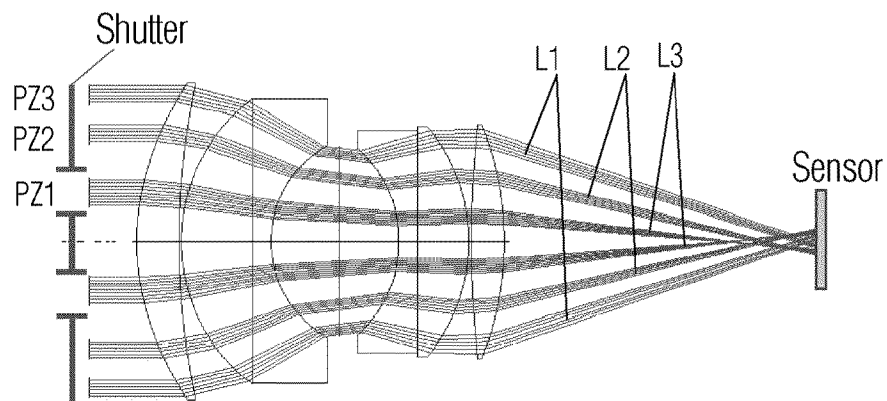
[Fig. 15b]



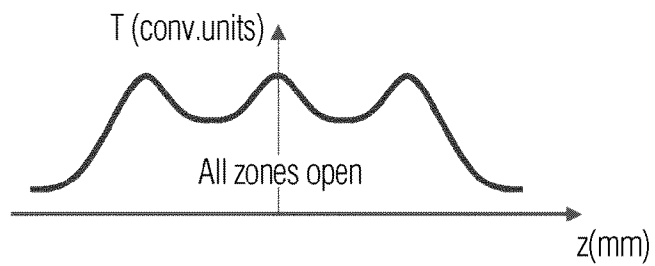
[Fig. 15c]



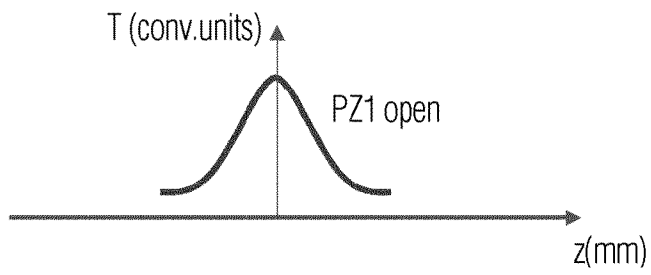
[Fig. 16a]



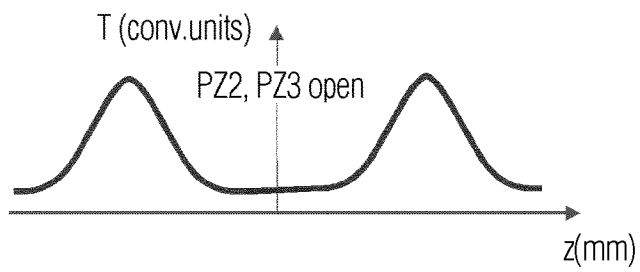
[Fig. 16b]



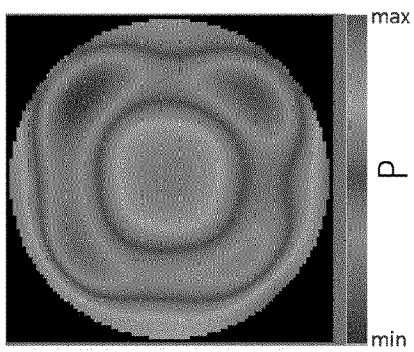
[Fig. 16c]



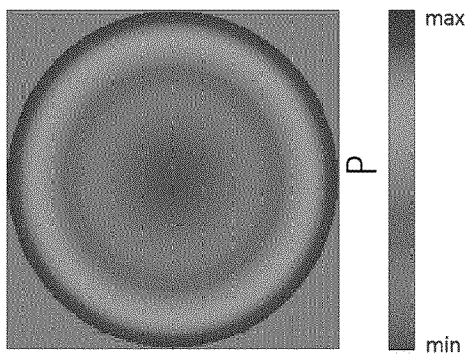
[Fig. 16d]



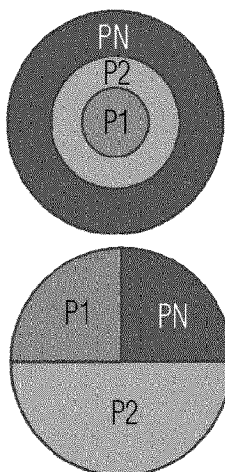
[Fig. 17a]



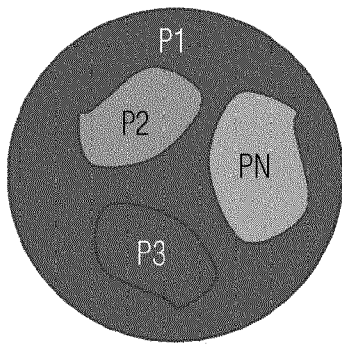
[Fig. 17b]



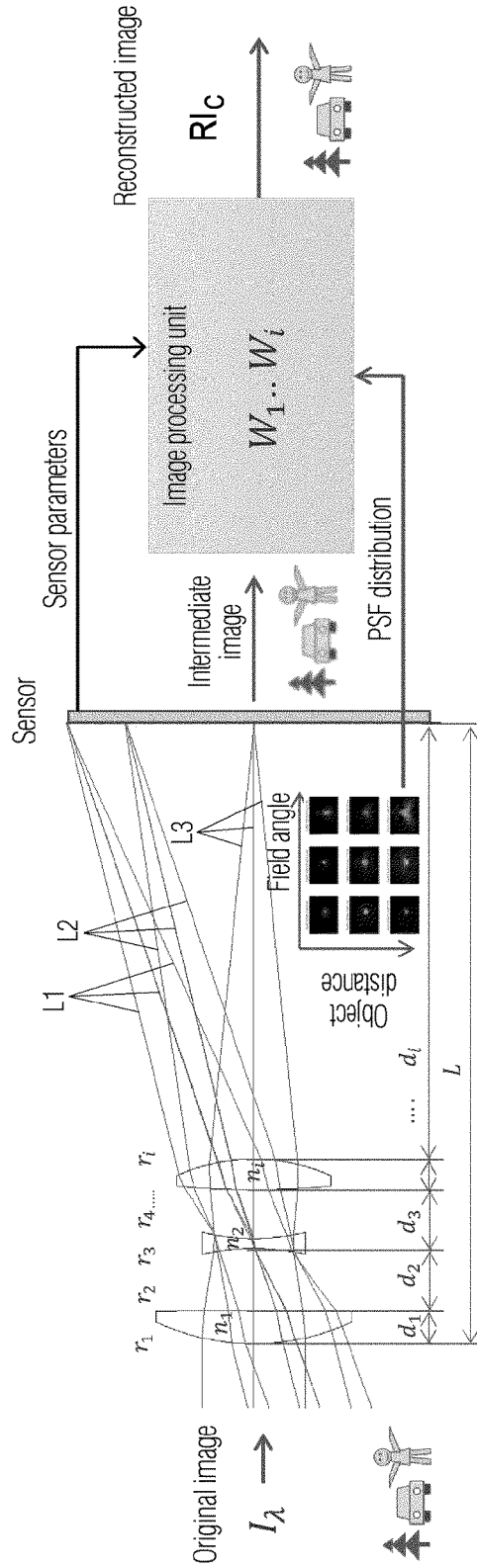
[Fig. 17c]



[Fig. 17d]



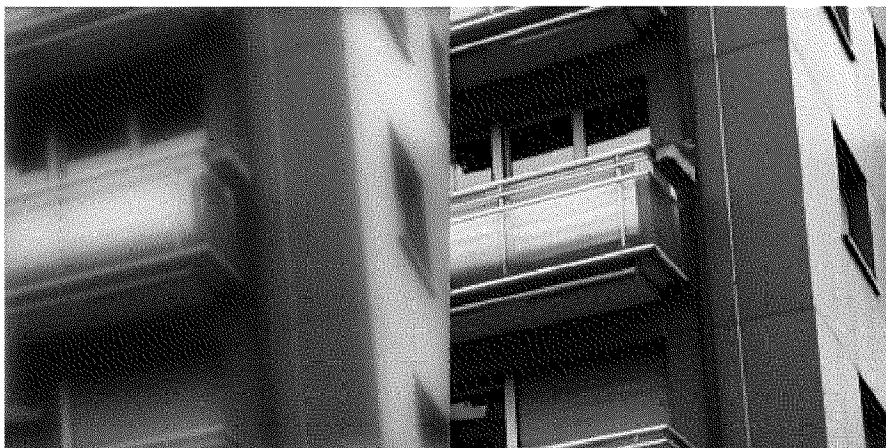
[Fig. 18]



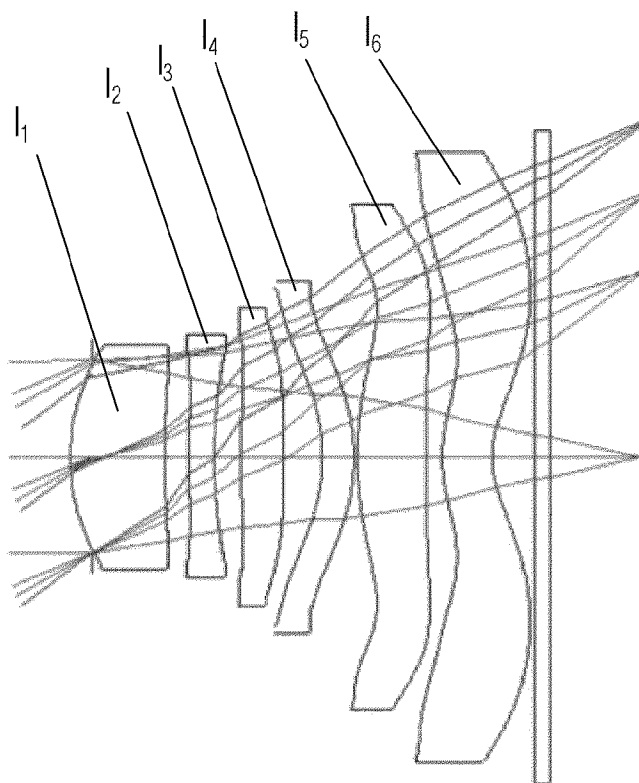
[Fig. 19a]



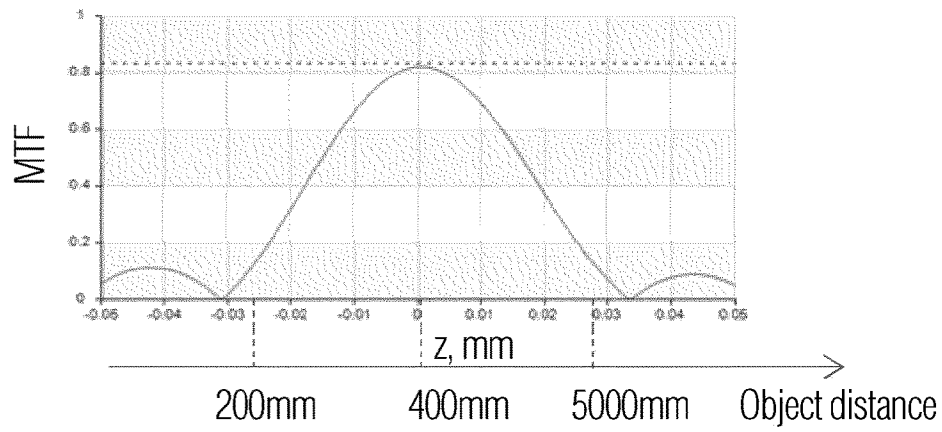
[Fig. 19b]



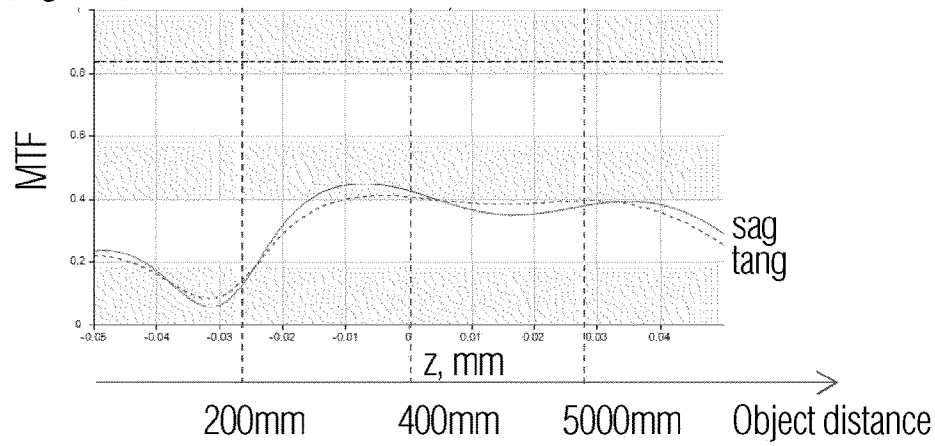
[Fig. 20a]



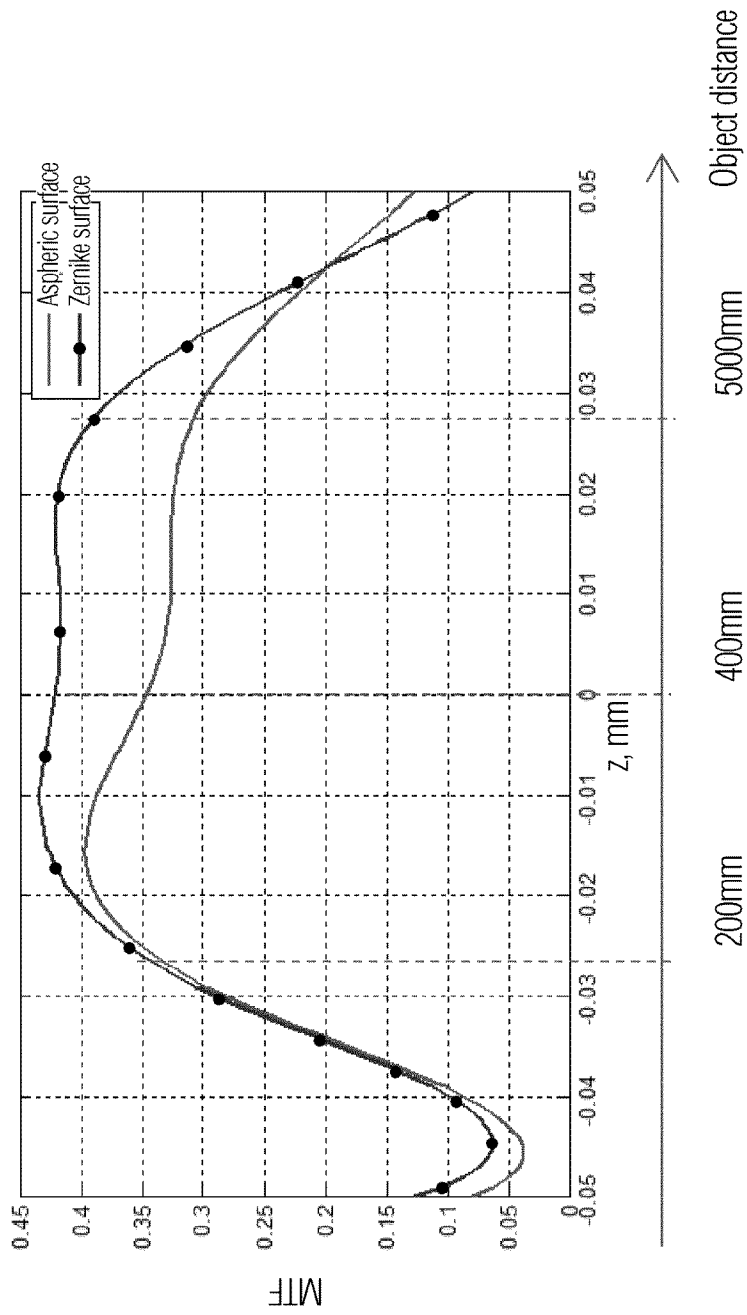
[Fig. 20b]



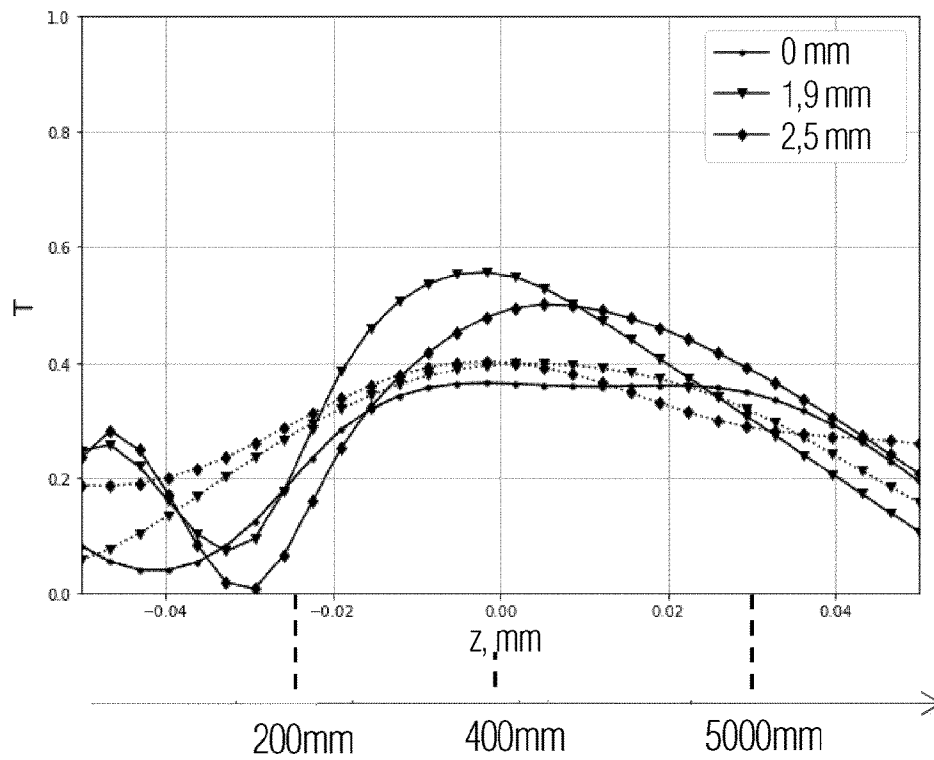
[Fig. 20c]



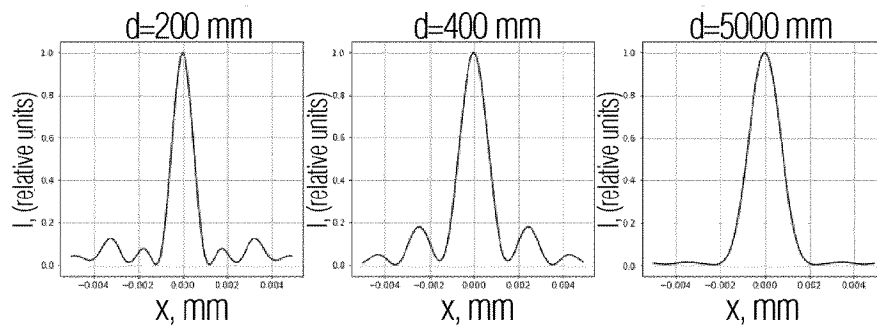
[Fig. 21]



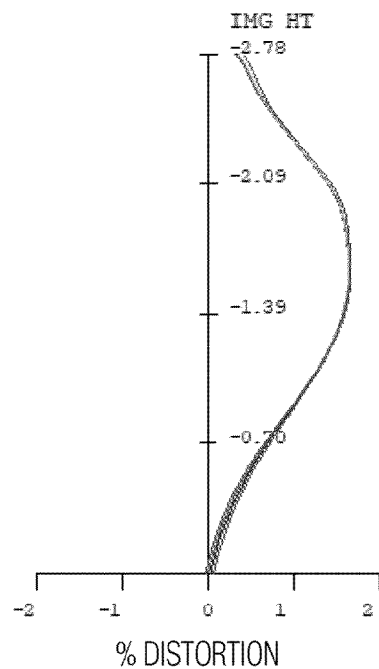
[Fig. 22a]



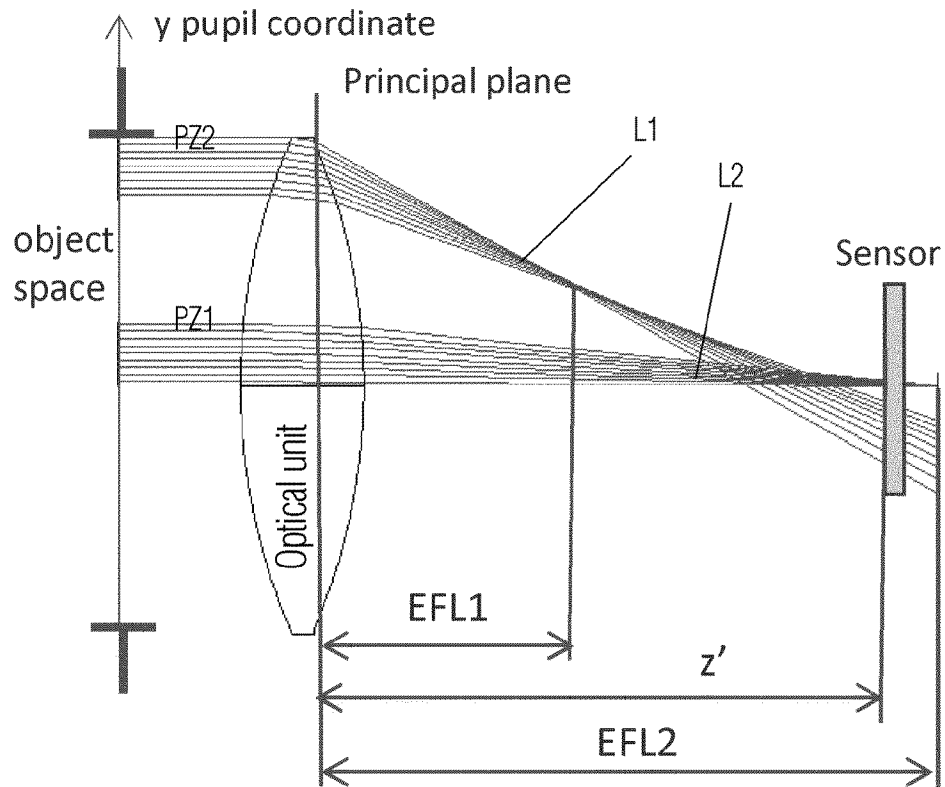
[Fig. 22b]



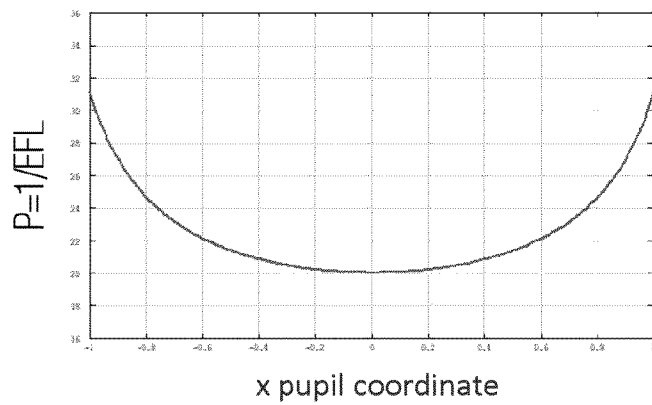
[Fig. 22c]



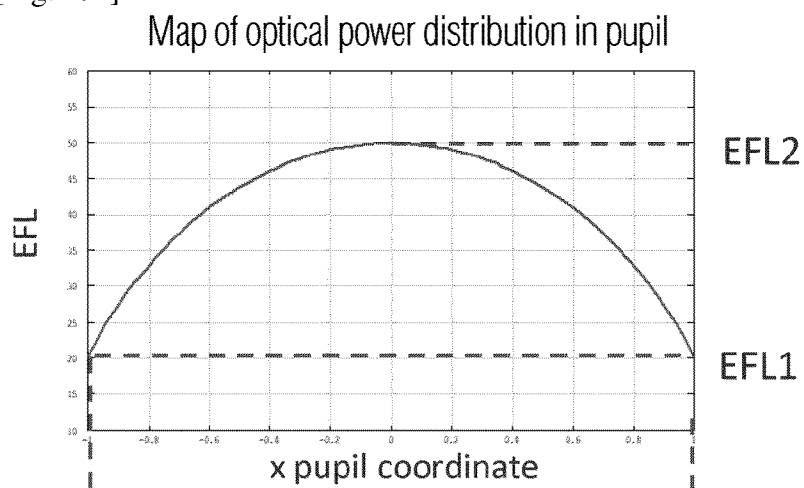
[Fig. 23a]



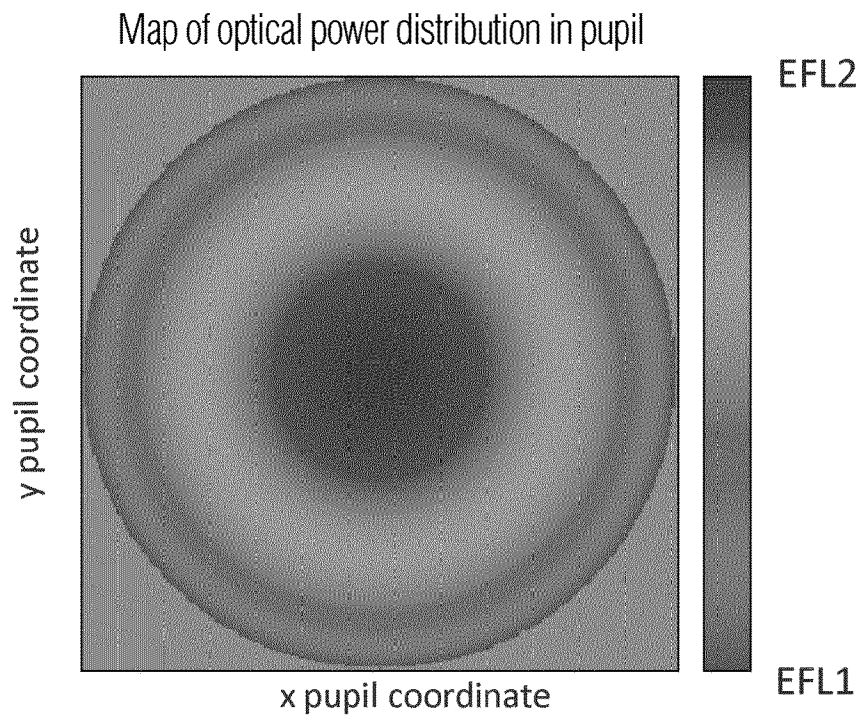
[Fig. 23b]



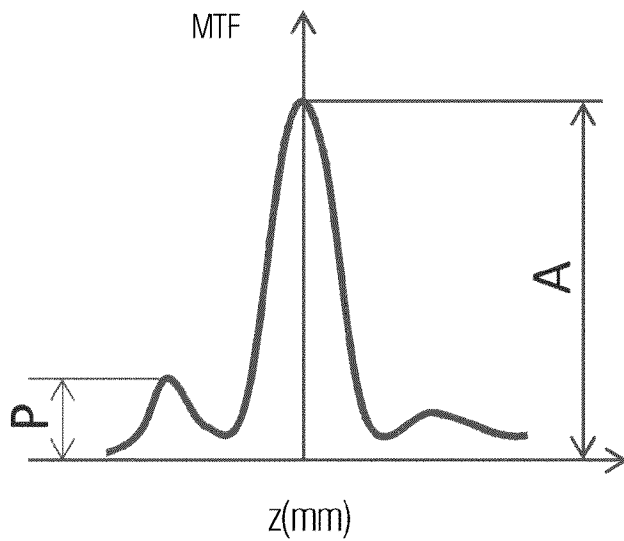
[Fig. 23c]



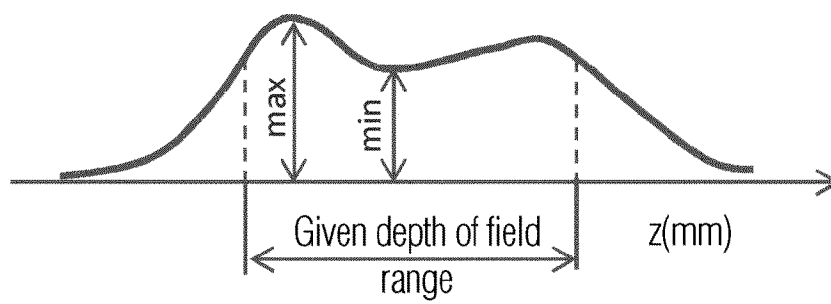
[Fig. 23d]



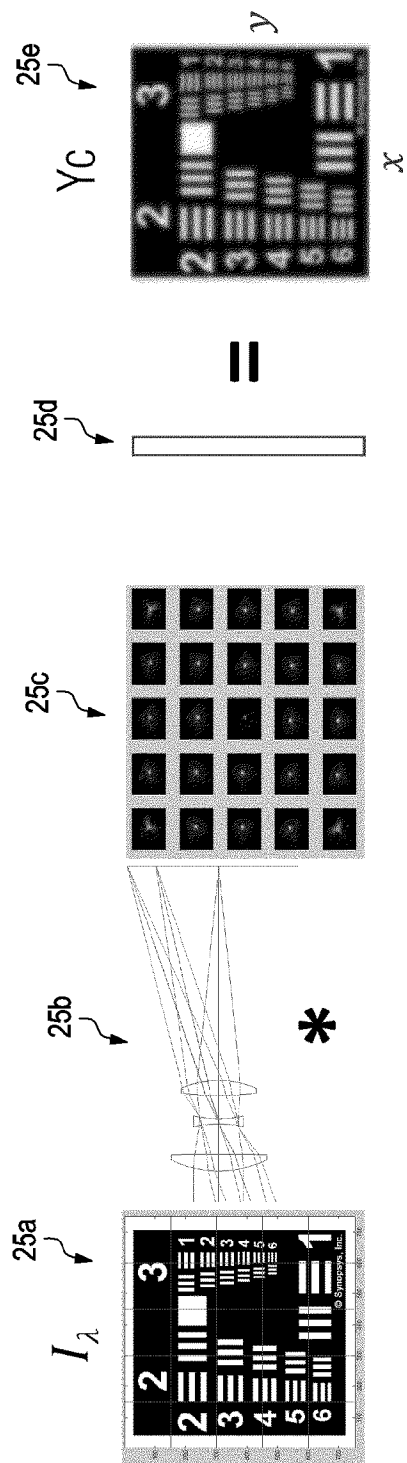
[Fig. 24a]



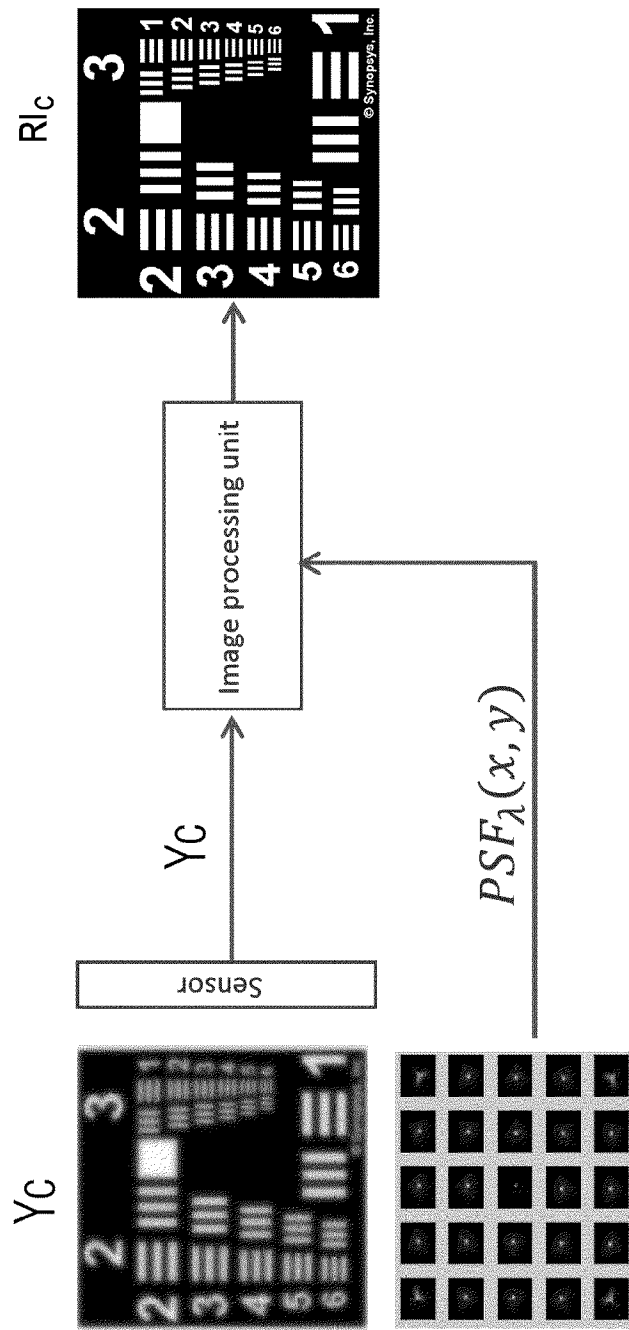
[Fig. 24b]



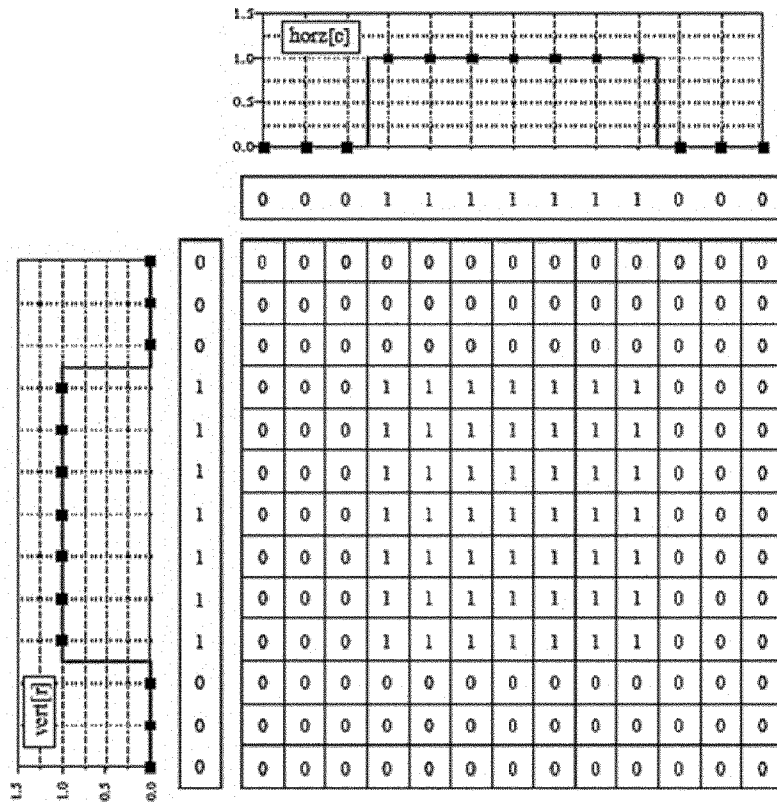
[Fig. 25]



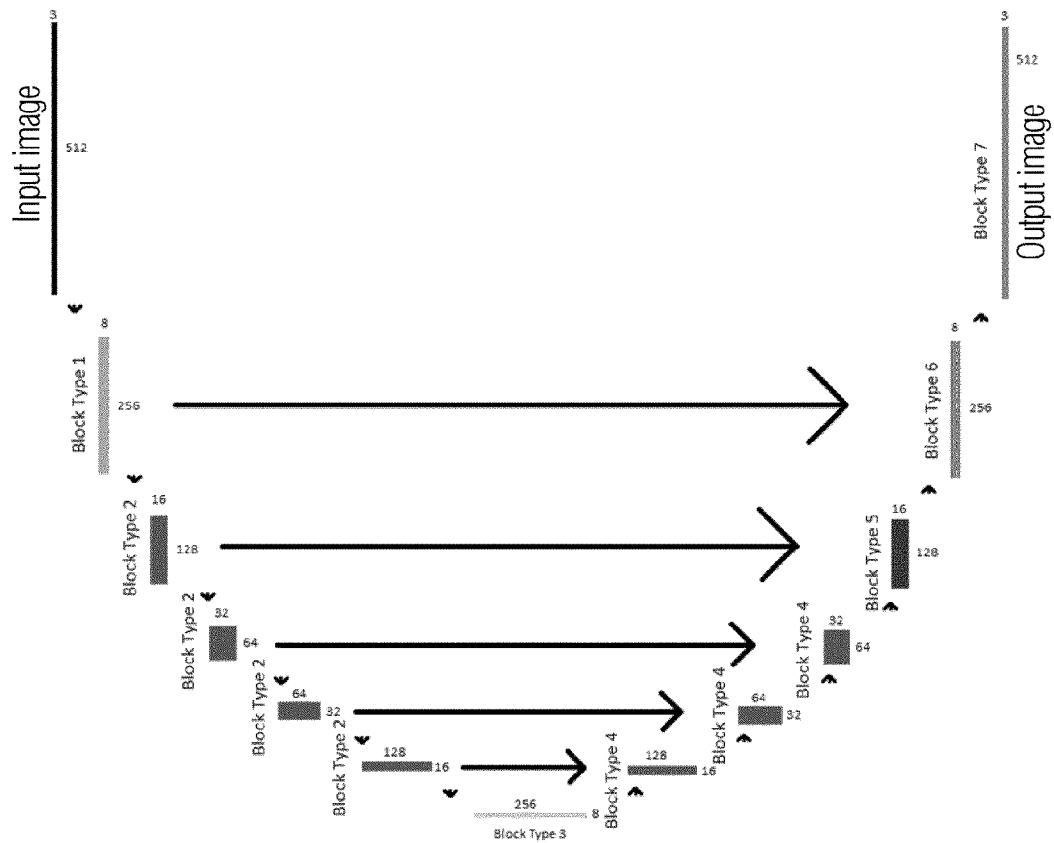
[Fig. 26]



[Fig. 27]



[Fig. 28]



INTERNATIONAL SEARCH REPORT

International application No.

PCT/KR2022/016053

A. CLASSIFICATION OF SUBJECT MATTER**G06T 7/557**(2017.01)i; **G06T 7/521**(2017.01)i; **G02B 27/00**(2006.01)i; **G02B 5/18**(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G06T 7/557(2017.01); G02B 13/18(2006.01); G02B 13/20(2006.01); G02B 27/00(2006.01); G03B 13/18(2006.01);
G06K 9/40(2006.01); H04N 5/217(2011.01); H04N 5/262(2006.01)

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

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: extended depth, blur, point spread function, distance, angle

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2006-0050409 A1 (NICHOLAS GEORGE et al.) 09 March 2006 (2006-03-09) paragraphs [0050]-[0053]; claim 1; and figure 1	1-15
A	US 2009-0297056 A1 (DAN LELESCU et al.) 03 December 2009 (2009-12-03) paragraphs [0074]-[0075]; claim 1; and figure 4	1-15
A	KR 10-1747844 B1 (LG INNOTEK CO., LTD.) 15 June 2017 (2017-06-15) paragraphs [0027]-[0033]; and figure 2	1-15
A	EP 1978394 A1 (GLOBAL BIONIC OPTICS PTY LTD.) 08 October 2008 (2008-10-08) paragraphs [0023]-[0026]; and figure 5	1-15
A	WO 2009-106996 A2 (GLOBAL BIONIC OPTICS, PTY LTD.) 03 September 2009 (2009-09-03) claims 1-10	1-15



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance

“D” document cited by the applicant in the international application

“E” earlier application or patent but published on or after the international filing date

“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&” document member of the same patent family

Date of the actual completion of the international search

31 January 2023

Date of mailing of the international search report

31 January 2023

Name and mailing address of the ISA/KR

Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon
35208, Republic of Korea

Facsimile No. +82-42-481-8578

Authorized officer

YANG, Jeong Rok

Telephone No. +82-42-481-5709

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/KR2022/016053

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
US	2006-0050409	A1	09 March 2006	CN	100594398	C	17 March 2010
				CN	101048691	A	03 October 2007
				EP	1789830	A2	30 May 2007
				JP	2008-511859	A	17 April 2008
				KR	10-2007-0057231	A	04 June 2007
				US	2008-0075386	A1	27 March 2008
				US	7336430	B2	26 February 2008
				WO	2006-028527	A2	16 March 2006
				WO	2006-028527	A3	18 January 2007
US	2009-0297056	A1	03 December 2009	US	8131097	B2	06 March 2012
KR	10-1747844	B1	15 June 2017	KR	10-2012-0039855	A	26 April 2012
EP	1978394	A1	08 October 2008	CN	101681021	A	24 March 2010
				CN	101681021	B	01 February 2012
				EP	2140301	A2	06 January 2010
				JP	2010-524073	A	15 July 2010
				JP	5153862	B2	27 February 2013
				US	2010-0110275	A1	06 May 2010
				US	8594388	B2	26 November 2013
				WO	2008-122888	A2	16 October 2008
				WO	2008-122888	A3	19 March 2009
WO	2009-106996	A2	03 September 2009	CN	101978304	A	16 February 2011
				EP	2096483	A1	02 September 2009
				JP	2011-518341	A	23 June 2011
				JP	2012-518341	A5	05 April 2012
				KR	10-1610975	B1	08 April 2016
				KR	10-2011-0033816	A	31 March 2011
				US	2010-0328517	A1	30 December 2010
				US	8488044	B2	16 July 2013
				WO	2009-106996	A3	22 October 2009