(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
19 December 2024 (19.12.2024)

WIPO | PCT

(10) International Publication Number
WO 2024/256320 A1

(51) International Patent Classification:
G02B 1/00 (2006.01) *G02B 5/18* (2006.01)

(21) International Application Number:
PCT/EP2024/065897

(22) International Filing Date:
10 June 2024 (10.06.2024)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10 2023 115 665.9 15 June 2023 (15.06.2023) DE

(71) Applicant: **AMS-OSRAM ASIA PACIFIC PTE. LTD.** [SG/SG]; 7000 Ang Mo Kio Avenue 5, #02-00, Singapore 569877 (SG).

(72) Inventors: **HALLAL, Bassam**; Alte Landstrasse, 168, 8800 Thalwil (CH). **BRUECKNER, Andreas**; Finkenstraße 16a, 82194 Gröbenzell (DE). **NIKETIC, Nemanja**; Sonnenbergstrasse 39, 8800 Thalwil (CH).

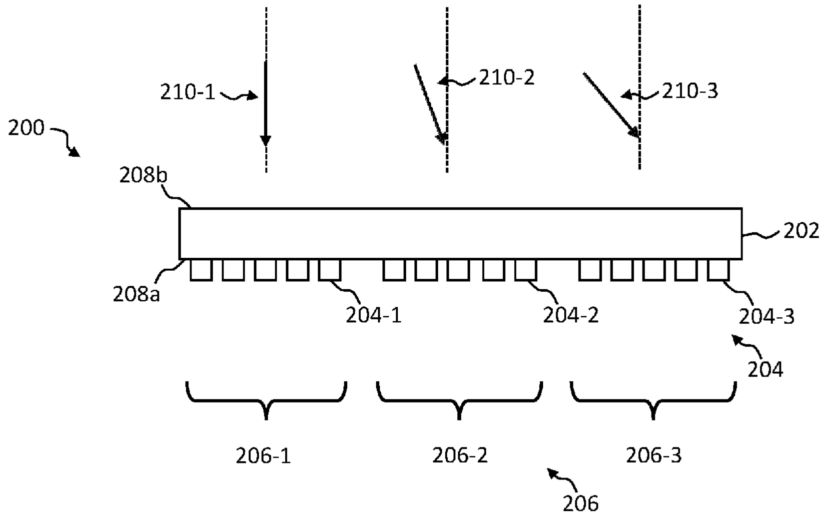
(74) Agent: **VIERING, JENTSCHURA & PARTNER MBB**; Am Brauhaus 8, 01099 Dresden (DE).

(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, MU, 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, SC, SD, SL, ST,

(54) Title: OPTICAL METALENS

FIG.2A



(57) **Abstract:** The present disclosure relates to a metalens (200) including: a metasurface (208a) with a plurality of regions (206), wherein the plurality of regions (206) include, at least: a first region (206-1) with a plurality of first nanostructures (204-1) configured in accordance with a first angle of incidence (210-1) of light arriving on the metasurface (208a), such that the first nanostructures diffract a maximum amount of light in the first diffraction order for light arriving onto the first region (206-1) at the first angle of incidence (210-1); and a second region (206-2) with a plurality of second nanostructures (204-2) configured in accordance with a second angle of incidence (210-2) of light arriving on the metasurface (208a), such that the second nanostructures diffract a maximum amount of light in the first diffraction order for light arriving onto the second region (206-2) at the second angle of incidence (210-2).

WO 2024/256320 A1

[Continued on next page]

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))*

OPTICAL METALENS

Technical Field

[0001] The present disclosure relates generally to an optical metalens including a plurality of zones each configured according to a respective angle of incidence of incoming light, and to methods thereof (e.g., a method of fabricating an optical metalens).

Background

[0002] In general, optical components to manipulate light are a key part in a variety of devices such as sensors, cameras, display devices, medical equipment, and the like. In particular, optical lenses allow shaping a light beam according to a desired application, e.g. to focus the light beam towards a particular direction, to collimate a light beam for uniform light emission, etc. In view of the constant trend towards miniaturization, a type of lenses gained attention in the recent years, the so-called metalenses. A metalens is a flat lens technology including nanostructures that are capable of modify properties of incoming light to engineer the wavefront and achieve the same functionalities as a traditional lens with a lighter and more compact design. In particular, a metalens may be thinner than a traditional lens, thus making it an attractive solution for applications in modern electronic devices, such as mobile communication devices, virtual reality systems, augmented reality systems, and the like. Improvements in metalenses may thus be of particular relevance for the further advancement of several technologies.

Brief Description of the Drawings

[0003] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various aspects of the invention are described with reference to the following drawings, in which:

FIG.1A shows an imaging device in a schematic view, according to various aspects;

FIG.1B shows a metalens in a schematic representation, according to various aspects;

FIG.2A shows a metalens including a plurality of zones in a schematic representation, according to various aspects;

FIG.2B shows a nanostructure of a metalens in a schematic representation, according to various aspects;

FIG.2C shows a plurality of zones of a metalens in a schematic representation, according to various aspects;

FIG.2D and FIG.2E show an exemplary arrangement of the zones in the metalens in a schematic representation, according to various aspects;

FIG.3 shows an optical system including the metalens in a schematic representation, according to various aspects; and

FIG.4 shows a schematic flow diagram of a method of fabricating a metalens according to various aspects.

Description

[0004] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and aspects in which the invention may be practiced. These aspects are described in sufficient detail to enable those skilled in the art to practice the invention. Other aspects may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various aspects are not necessarily mutually exclusive, as some aspects may be combined with one or more other aspects to form new aspects. Various aspects are described in connection with methods and various aspects are described in connection with devices (e.g., an optical metalens, an optical system). However, it is understood that aspects described in connection with methods may similarly apply to the devices, and vice versa.

[0005] In general, imaging devices capable of capturing three dimensional (3D) information within a scene are of great importance for a variety of application scenarios. A prominent example is the use of tracking sensors for augmented reality (AR) and virtual reality (VR) applications. For example, a world-tracking sensor allows sensing the environment around the user wearing the sensor, and further allows sensing where the user is heading (e.g., similar to head tracking). As another example, a gesture-tracking sensor allows sensing where the user’s fingers and hands are, and in which form they are moving. As a further example, an eye-tracking sensor allows sensing where exactly the user is looking at and what the user is focusing on. Sensing data from the tracking sensors enable a variety of functionalities in the AR and VR context, such as presenting information to the user, executing commands based on a gesture or a gaze of the user, and the like. Other fields of application may include face recognition and authentication in modern smartphones, factory automation for Industry 5.0, authentication systems for electronic payments, internet of things (IoT) environments, and the like.

[0006] Tracking sensors for augmented reality and/or virtual reality may be camera based visual sensors operating in the visible spectral bandwidth and/or near infrared (NIR) spectral bandwidth, in view of the human sense of sight. An imaging device for such applications may usually include a compact camera module (CCM) for sensing light and generating corresponding sensing data. With the advancements of new generations of imaging devices, there is a constant demand for a miniaturization of their mechanical, optical, and electrical components.

[0007] In this context, a camera-based tracking sensor may usually include a CMOS image sensor (CIS), where CMOS stands for Complementary Metal-Oxide Semiconductor. The desirable properties for a CMOS image sensor may include a reduced (global shutter) pixel size, an increased quantum efficiency, e.g. in the NIR spectral bandwidth, and a simple integration in an integrated circuit, which may allow obtaining a reduced chip size and a reduction in costs. A camera based tracking sensor may further include an optical lens module to collect light from the field of view of the sensor and direct the collected light to the image sensor (e.g., the CMOS image sensor). In this context, metalenses have emerged as a promising alternative to traditional lenses, in view of their flat geometry, small thickness, and overall compact design, which may allow achieving a reduced footprint of the optical module. In addition, the optical properties of a metalens may be tailored in a more flexible manner compared to a traditional lens, thus allowing an adaptation of the optical function to the specific requirements of a given application.

[0008] The present disclosure is related to an adapted design of a metalens that allows increasing the efficiency of the light manipulation by taking into consideration the angle of incidence with which the light impinges onto the metalens. The metalens proposed herein may be subdivided into a plurality of regions (also referred to herein as zones), and the configuration of the array of nanostructures present in each region may be adapted according to a respective angle of incidence of incoming light. The proposed configuration increases the efficiency of the metalens by optimizing the properties of the array of nanostructures according to the expected angle of incidence of incoming light during an operation of the metalens.

[0009] Illustratively, the present disclosure may be based on the realization that in operation (e.g., during a sensing process in an imaging device) light may not arrive with the same angle of incidence on the whole surface of the metalens. Rather, light may be delivered to the metalens in such a way that the (meta)surface of the metalens is illuminated by light rays impinging onto the surface at different angles. This may be the case, for example, in a camera system in which optical apertures are present in the optical path through which light propagates. An optical aperture may cause diffraction of light, thus causing the light to travel towards the metalens at a plurality of different angles.

[0010] In a conventional configuration, the nanostructures that define the metalens are characterized and configured for a normal angle of incidence of the incoming light, which may be the simplest and most straightforward scenario. Such characterization and configuration, however, does not take into account the observations above, so that when light impinges onto the metalens at angles other than the normal angle, the metalens may offer a sub-optimal performance. Illustratively, the nanostructures may still impart a phase change to the light, but since their configuration has been designed based on a normal angle of incidence the efficiency of light manipulation may degrade compared to an ideal case.

[0011] The present disclosure may be related to a metalens designed having in mind that in operation light may impinge onto different regions of the metalens at a different angle of incidence. The proposed configuration may thus include configuring (and characterizing) the nanostructures in each region according to a respective angle of incidence of the incoming light, to provide a uniform performance in terms of phase change over the entire surface of the metalens, and increasing the overall efficiency of the optical function provided by the metalens.

[0012] According to various aspects, a metalens may include: a metasurface with a plurality of regions, wherein the plurality of regions include at least: a first region with a plurality of first nanostructures configured in accordance with a first angle of incidence of light arriving on the metasurface; and a second region with a plurality of second nanostructures configured in accordance with a second angle of incidence of light arriving on the metasurface.

[0013] According to various aspects, a metalens may include: a metasurface with a plurality of regions, wherein each region comprises an array of nanostructures with a respective (average) spacing, wherein the (average) spacing of each array is within a corresponding range unique to that array.

[0014] According to various aspects, an optical system may include: a metalens configured as described herein; and an optical element (e.g., an optical aperture) configured to receive input light and diffract the input light into output light at a plurality of output angles, wherein the optical element and the metalens are disposed such that the first region of the metasurface receives output light at the first angle of incidence, and the second region of the metasurface receives output light at the second angle of incidence.

[0015] The configuration described herein may thus be understood as a “zoning” of the surface of the metalens, in which different zones are configured according to a respective angle of incidence of incoming light. The zone-configuration allows thus engineering the optical response of the metalens according to an expected behavior during an operation of the metalens (e.g., during an operation of a tracking sensor including the metalens) and enhance the overall efficiency of light manipulation.

[0016] In the context of the present disclosure, the term “metalens” may be used as commonly understood in the art to describe a lens that manipulates light by means of an array of nanostructures rather than via refraction. A metalens may thus include a so-called metasurface with the array of nanostructures. The nanostructures may be configured to manipulate the light impinging onto the metasurface by imposing a phase change onto the phase of the light. The nanostructures may thus modify the wavefront of the light to achieve a desired optical function, e.g. focusing, collimation, and the like. The nanostructures may be disposed over the metasurface to create a phase change profile that is designed to implement the desired optical function. A “metalens” may also be referred to herein as “meta-lens”, “meta lens”, or “metasurface lens”.

[0017] In the context of the present disclosure particular reference may be made to applications of a metalens configured as described herein for light detection purposes. Illustratively, particular reference may be made to a use of the lens for focusing light onto an image sensor (e.g., a CMOS sensor). This application may be a relevant use case for the proposed metalens, e.g. in the context of AR- or VR-applications. It is however understood that in principle a metalens configured as described herein may also be used at the emitter-side of an optical system, e.g. to manipulate the wavefront of emitted light. Furthermore, particular reference may be made to the use of the metalens in a tracking sensor, but it is understood that the metalens may be introduced (e.g., integrated) in other types of imaging devices in which an overall miniaturization of the optical module may be advantageous. Further examples of imaging devices in which the metalens may be integrated may include a time-of-flight sensor, a stereo vision sensor, a disparity-based sensor, and the like.

[0018] **FIG.1A** shows an imaging device 100 in a schematic representation, according to various aspects. The imaging device 100 may be an exemplary device that includes one or more image sensors, e.g. for light detection, imaging, face recognition, and the like. It is understood, that the imaging device 100 provides an exemplary and simplified configuration of a possible application scenario of a metalens as described herein. In an exemplary configuration, the imaging device 100 may be a tracking sensor, e.g. the imaging device 100 may be configured to track one or more features (one or more elements) in a field of view 110 of the imaging device 100, as discussed in further detail below. As other examples, the imaging device 100 may be configured as a time-of-flight sensor, a proximity sensor, a stereo vision sensor, and the like. The representation of the imaging device 100 may be simplified for the purpose of illustration, and the imaging device 100 may include additional components with respect to those shown, such as one or more filters, one or more amplifiers, etc.

[0019] The imaging device 100 may include an image sensor 102. The image sensor 102 may be configured to be sensitive for light in a predefined wavelength range, e.g. the visible range (e.g., from about 380 nm to about 700 nm), infrared and/or near-infrared range (e.g., in the range from about 700 nm to about 5000 nm, for example in the range from about 860 nm to about 1600 nm, for example at 940 nm), or ultraviolet range (e.g., from about 100 nm to about 400 nm). Illustratively, the image sensor 102 may be configured to convert light energy (illustratively, photons) of light impinging onto the image sensor 102 in electrical energy (e.g., in a current, illustratively a photo current). In general, the imaging device 100 may have compact dimensions, e.g. a small footprint size. For example, the image sensor 102 may be a chip-scale packaged image sensor.

[0020] The geometry (e.g., the shape and lateral dimensions) of the image sensor 102 may be adapted according to the system requirements, e.g. according to an overall dimension of the imaging device 100, according to fabrication constraints, etc. The image sensor 102 may thus have any suitable shape, such as a rectangular shape, a square shape, or even asymmetric shapes. In general, the image sensor 102 may include a plurality of pixels, e.g. a first plurality of pixels N_x defining a first dimension, and a second plurality of pixels N_y defining a second dimension. In various aspects, the image sensor may include a two-dimensional array of pixels. A number of pixels N_x, N_y in each direction, as well as a pixel pitch may be adapted depending on the desired dimension of the image sensor 102. As a numerical example, the image sensor 102 may include at least 10^4 pixels (e.g., 100x100 pixels), for example at least $4x10^4$ pixels (e.g., 200x200 pixels). As another numerical example, the image sensor 102 may have a lateral dimension (e.g., a width) in the range from 1 mm to 10 mm, for example in the range from 2 mm to 5 mm.

[0021] According to various aspects, the image sensor 102 may be configured according to CMOS-technology, e.g. the image sensor 102 may be a CMOS image sensor. In this configuration, the image sensor 102 may include a plurality of CMOS pixels, each including a photodetector that accumulates an electrical charge based on the amount of light impinging onto the photodetector. As another exemplary configuration, the image sensor 102 may be configured according to Charged Coupled Device (CCD) technology, e.g. the image sensor 102 may be a CCD image sensor. In this configuration, the image sensor 102 may include a plurality of CCD pixels with a photoactive region and a transmission region.

[0022] In the imaging device 100, an optical module 104 may define the field of view 110 of the image sensor 102. Illustratively, the optical module 104 may be configured to collect light and direct (e.g., focus) the collected light onto the image sensor 102, e.g. on one or more of the pixels of the image sensor 102. According to various aspects, the optical module 104 may include a metalens 108, e.g. configured as proposed herein (see also FIG.2A to FIG.2D), to focus the received light onto the image sensor 102. The image sensor 102 may be disposed in the image plane of the metalens 108.

[0023] The imaging device 100 may further include a processor 106 configured to receive image data from the image sensor 102 and carry out processing of the image data. For example, the processor 106 may be coupled with an analog-to-digital converter configured to convert an analog signal from the image sensor 102 (e.g., a photo current) into a digital signal to enable digital processing at the processor 106. The processor 106 may be configured to analyze and manipulate the image data according to the function provided by the imaging device 100.

[0024] As an example, the processor 106 may be configured to carry out a tracking of an element in the field of view 110. Illustratively, the processor 106 may be configured to follow an evolution of a spatial position of the element over time, e.g. to associate two-dimensional coordinates or three-dimensional coordinates corresponding to a position of the element to a respective time point. The tracked element may be any suitable feature or object of interest, such as the hand of a user, the eyes of a user, a vehicle, an animal, etc.

[0025] As another example, the processor 106 may be configured to calculate a time-of-flight associated with the received light. The processor 106 may receive a signal indicative of an emission time of the light and may identify a time of arrival of light at the imaging device 100 based on the signal delivered by the image sensor 102. This configuration may be provided, for example, for mapping the presence of objects in the field of view 110, and their properties such as distance from the device 100, speed, direction of motion, and the like.

[0026] As a further example, the processor 106 may be configured to determine (e.g., estimate, measure) the distortion of a predefined light pattern (e.g., a grid of light dots for example). This configuration may be provided, for example, for face-recognition applications, in which the distortion of the emitted pattern is associated to the profile of an object (e.g., a person) in the field of view 110 of the imaging device 100. For example, the processor 106 may be configured to reconstruct a shape of the object (e.g., a face) based on the distorted pattern.

[0027] In an exemplary configuration, the imaging device 100 may further include a light emission system (not shown) configured to emit light into the field of view 110. Illustratively, the light emission system may emit light in a field of illumination that overlaps (fully, or at least in part) with the field of view 110. The light emission system may include emitter optics (e.g., one or more lenses, one or more mirrors, and the like) and a light source configured to emit light in a predefined wavelength range. As an example, the light source may be or include a laser source, e.g. a Vertical Cavity Surface Emitting Laser (VCSEL) or a VCSEL-array. The light source may be configured to emit light having a predefined wavelength, illustratively in the same wavelength range for which the image sensor 102 is sensitive.

[0028] The light source may be configured to emit light in any suitable manner depending on the overall configuration of the imaging device 100. As an example, the light source may emit continuous light. As another example, the light source may emit light in a pulsed manner (e.g., for time-of-flight measurements), e.g. the light source may emit a sequence of light pulses. As a further example, the light emission system may emit light according to a predefined pattern, e.g. a grid of light dots. In an exemplary configuration, the processor 106 may be configured to control the light emission by the light source, e.g. the processor 106 may be configured to instruct or cause the light emission, e.g. at a certain time point, at certain time intervals, in response to a certain event, and the like.

[0029] As mentioned above, the optical module 104 may include a metalens 108 for manipulating light, e.g., for focusing light onto the image sensor 102. In general, the basic principles and elements of a metalens are known in the art. **FIG.1B** shows an exemplary configuration of a metalens 150 to provide a brief description of some relevant aspects.

[0030] In general, the metalens 150 may include a plurality of nanostructures 154 arranged according to a predefined pattern to provide an optical function for manipulating light arriving on the metalens 150. The nanostructures 154 may be configured to impose a phase change to light incident on the nanostructures 154, as discussed in further detail below. By disposing the nanostructures 154 according to a certain pattern the metalens 150 may defined a profile for the phase change that implements the desired manipulation of the incident light.

[0031] By way of illustration, the properties and the arrangement of the nanostructures 154 may be selected to create a target phase profile on the surface of the metalens 150. A first step in designing a metalens 150 may thus include defining the target phase profile to be provided via the nanostructures 154. The target phase profile may reproduce the desired light manipulation, e.g. as it would be achieved by a corresponding traditional lens. As examples, the target phase profile may be configured to reproduce the function of a converging lens, of a diverging lens, of a collimating lens, and the like. Illustratively, the target phase profile may correspond to the light manipulation that the curvature of the corresponding traditional lens would achieve. The target phase profile may be designed according to analytical equations describing the corresponding lens, or via simulations, as known in the art.

[0032] Once the target phase profile has been designed, the next step may include characterizing the nanostructures 154 to associate the properties of the nanostructures 154 to corresponding light manipulation, e.g. to a corresponding phase change. For example, the next step may include a parameter scan to associate geometrical properties of the nanostructures 154, e.g. height, width, radius, etc. to a corresponding phase change that the nanostructure imposes onto incident light. This characterization step allows building a library in which each phase change (e.g., in the range from 0 to 2π) is associated with corresponding geometrical properties of a nanostructure.

[0033] After the characterization the nanostructures 154 are disposed on a substrate 152 according to their properties to achieve the target phase profile. Illustratively, the target phase profile defines a distribution of nanostructures 154 according to their geometrical properties to achieve the desired optical function. The characterization thus allows creating an arbitrary phase profile on the surface of the metalens by placing the nanostructures 154 at the corresponding positions based on the respective induced phase change.

[0034] A metalens 150 (and corresponding metasurface) may be fabricated with techniques analogous to semiconductor technology, e.g. with CMOS fabrication techniques. For example, the fabrication of a metalens 150 may include one or more photolithography steps, e.g. the patterning of a photoresist to define a pattern for the nanostructures 154, a material deposition to form the nanostructures 154, the removal of the photoresist after the material deposition, and the like. As another example, the fabrication of a metalens 150 may include electron-beam lithography and material deposition, e.g. conformal deposition such as atomic layer deposition.

[0035] As mentioned above, in a conventional design, the characterization of a nanostructure to identify the corresponding phase change is carried out based on a normal angle of incidence of the incoming light. This approximation may hold in some scenarios, however does not achieve an optimal efficiency of optical manipulation in applications in which light impinges onto the metalens at different angles of incidence. Illustratively, in a conventional approach the nanostructures are disposed on the substrate without taking into consideration that in operation nanostructures disposed in different locations may receive light coming at different angles.

[0036] The present disclosure may provide a metalens in which the distribution of the nanostructures on the surface takes into consideration the expected angle of incidence of incoming light during an operation of the metalens. In particular, the proposed configuration includes a metalens with a plurality of regions (or zones) each dedicated to a corresponding angle of incidence of incoming light. The proposed configuration thus characterizes the nanostructures in different regions to optimize the corresponding phase change for light that impinges onto the nanostructure at the corresponding incidence angle. This configuration allows thus optimizing the optical response of the metalens.

[0037] **FIG.2A** shows a metalens 200 configured according to the strategy proposed herein in a schematic representation. In general, the metalens 200 may include a plurality of nanostructures 204 organized in different regions 206 according to an expected angle of incidence of incoming light onto the region 206. Illustratively, the metalens 200 may be an adapted configuration of the metalens 108, 150 discussed in relation to FIG.1A and FIG.1B. In some aspects, an imaging device (e.g., the imaging device 100) may include one or more metalenses 200, e.g. for light detection and/or light emission.

[0038] As shown in FIG.2A, the metalens 200 may include a substrate 202, and the nanostructures 204 may be disposed (e.g., formed, or integrated) on the substrate 202. The substrate 202 may include a first surface 208a and a second surface 208b opposite to the first surface 208a. The metalens 200 may include a metasurface with the plurality of nanostructures 204 on one of the (main) surfaces of the substrate 202, e.g. on the first surface 208a. In an exemplary configuration, the metalens 200 may further include a coating on the other (main) surface of the substrate 202, e.g. on the second surface 208b. The coating may be a protective coating for the metalens 200. As an example, the coating may be an anti-reflective coating to suppress reflection of light with wavelength in a predefined wavelength range.

[0039] The substrate 202 may be configured to allow transmission of light, e.g. in a predefined wavelength range in which the metalens 200 operates (also referred to herein as operating wavelength range of the metalens 200). Illustratively, the substrate 202 may be configured to allow light (with wavelength in the predefined range) to pass through. The predefined wavelength range may be selected according to a desired application of the metalens 200. As an example, the predefined wavelength range may be the visible range, infrared and/or near-infrared range, or ultraviolet range, as discussed in relation to FIG.1A. For example, the predefined wavelength range may be or include a sub-band in the near-infrared wavelength range, e.g. a sub-band centered around 940 nm. Such wavelength range may be of particular interest for applications in face recognition, virtual reality, or augmented reality. It is however understood that in principle the metalens 200 (and substrate 202) may be adapted for operation in any suitable wavelength range.

[0040] Illustratively, the (optical) substrate 202 may provide mechanical support to the metasurface of the metalens 200. The substrate 202 may include or may be made of any suitable material to provide sufficient support for the metalens and to allow transmission of light in the desired wavelength range. As examples, the optical substrate 202 may include or may consist of glass, such as borosilicate glass, or plastic (e.g., a transparent polymer). As other examples, the substrate 202 may include or may consist of an oxide, a nitride, an oxynitride, and the like. In some aspects, the optical substrate 202 may be configured to filter out light with wavelength outside a predefined wavelength range. For example, the material of the substrate may be transmissive only in the desired wavelength range. As another example, the optical substrate 202 may have a coating configured to block light with wavelength outside the predefined wavelength range. In general, the dimensions of the optical substrate 202 may be adapted based on the desired use case, e.g. based on the overall dimensions of the metalens or of the corresponding imaging device in which the metalens 200 is integrated.

[0041] In general, the metalens 200 may be configured to provide any suitable optical function to manipulate incident light. In a preferred configuration, the nanostructures 204 may be configured to define a phase profile on the metasurface of the metalens that causes a focusing of the light. This configuration may be suitable for imaging applications. It is however understood that in principle the nanostructures 204 may be configured to define a phase profile on the metasurface that causes other types of light manipulation, e.g. a collimation of the light, a diverging of the light, etc. As shown in FIG.2A, in operation the incoming light may propagate through the substrate 202 before reaching the metasurface 208a. The aspects discussed herein may also apply in a corresponding manner to the scenario in which the metalens 200 is oriented such that in operation the incoming light reaches first the metasurface 208a and then propagates through the substrate 202. In an exemplary configuration, the metalens 220 may include exactly one metasurface 208a.

[0042] According to the proposed configuration, the metasurface 208a of the metalens 200 may include a plurality of regions 206. In the exemplary configuration in FIG.2A, the metalens 200 may include a first region 206-1, a second region 206-2, and a third region 206-3. It is however understood that a metalens configured as proposed herein may be subdivided in any suitable number of regions, e.g. two, three, four, five, ten, or more than ten, according to a desired granularity for the light manipulation based on the angle of incidence.

[0043] Each region 206 may include respective plurality of nanostructures 204, e.g. first nanostructures 204-1 in the first region 206-1, second nanostructures 204-2 in the second region 206-2, third nanostructures 204-3 in the third region 206-3, etc. According to the proposed configuration, the nanostructures 204 in each region 206 may be configured in accordance with a respective angle of incidence of light impinging on the metalens 200 (and accordingly, on the metasurface 208a). Thus, the plurality of first nanostructures 204-1 may be configured according to a first angle of incidence 210-1 of light incident on the metalens 200, the plurality of second nanostructures 204-2 may be configured according to a second angle of incidence 210-2 of light incident on the metalens 200, the plurality of third nanostructures 204-3 may be configured according to a third angle of incidence 210-3 of light incident on the metalens 200, etc.

[0044] According to various aspects, the angle of incidence of incoming light may be defined with respect to the normal to the surface of the metalens 200, e.g. with respect to the normal to the surface 208a, 208b of the substrate 202. The angle of incidence may thus describe the angle that light rays form with the normal to the surface 208a, 208b. In some aspects, the angle of incidence of incoming light may be defined with respect to the optical axis of the metalens 200, e.g. may be the angle that light rays form with the optical axis.

[0045] Thus, the nanostructures 204 may be disposed on the metasurface 208a according to a phase profile to implement the desired optical function and, in addition, may be subdivided into regions within which the plurality of nanostructures are configured (and characterized) based on the expected angle of incidence of incoming light in that region (see also FIG.2C).

[0046] In principle, the type or properties of the individual nanostructures are not limited, provided that they may impart the desired phase change onto incident light. **FIG.2B** shows an exemplary nanostructure 220 in a schematic representation, according to various aspects (e.g., an exemplary realization of a nanostructure 204).

[0047] In general, a nanostructure 220 for a metalens 200 may be understood as a waveguide, or an antenna, which receives input light with a first phase and delivers output light with a second phase different from the first phase. Illustratively, the nanostructure 220 may impose a phase difference into the first phase to obtain the second phase for the output light. A phase difference may also be referred to herein as phase shift, or phase delta. A nanostructure 220 may thus function as a resonator to impart a phase change (e.g., in the range from 0 to 2π) to the incident light. Thus the nanostructure 220 (in combination with the other nanostructures) may cause a variation of the wavefront of the light incident on the metalens to provide an output wavefront having a desired profile, e.g. to focus light, collimate light, etc.

[0048] The term “nanostructure” may be used herein as commonly understood in the art to describe an element having dimensions less than 1 micron. In general, the dimensions of a nanostructure 220 may be related to the wavelength of interest of light incident on the metalens

200. As numerical examples, a nanostructure 220 as described herein may have a (first) lateral dimension 222 in the plane defined by the substrate of the metalens in the range from 50 nm to 500 nm, e.g. in the range from 100 nm to 200 nm. In an exemplary configuration, a nanostructure 220 may have a (second) lateral dimension 224 in the direction perpendicular to the substrate (illustratively, a height) greater than the extension in the plane of the substrate (illustratively, a width, or a length, or a diameter). As a numerical example, a nanostructure 220 may have a height in a range from 100 nm to 1000 nm, e.g. in the range from 200 nm to 600 nm. It is however understood that in principle the aspects discussed herein may also be applicable to structures with larger dimensions, e.g. also larger than 1 micron.

[0049] A nanostructure 220 may have any suitable geometry to impose a phase change on the incident light. In a preferred configuration, which may allow a simple and standardized fabrication process, a nanostructure 220 may be configured as a nano-pillar, illustratively as a nano-column. The base of the nano-pillar may have any suitable shape, e.g. the nano-pillar may have a circular base, a square base, a rectangular base, an elliptical base, a triangular base, or any polygonal base. However, in principle, a nanostructure 220 may also have other geometries suitable for scattering light and imposing the corresponding phase change. As another example, a nanostructure 220 may have a fin-like configuration.

[0050] A nanostructure 220 may include or may be made of any suitable material, e.g. selected according to the wavelength range in which the metalens should operate. As an example, a nanostructure 220 may include or may be made of a dielectric material, e.g. an oxide (such as titanium dioxide, tantalum pentoxide, and the like), a nitride (e.g., aluminum nitride, titanium nitride, gallium nitride, silicon nitride), a carbide (e.g., silicon carbide), etc. As another example, a nanostructure 220 may include or may be made of a polymer material, e.g. a silicone-based polymer. In general, the material of the nanostructure 220 may be selected to have a refractive index that allows wavefront manipulation. As a numerical example, the nanostructure 220 may include or may be made of a material with a refractive index greater than 1.0, e.g. a refractive index greater than 1.5, e.g. a refractive index greater than 2.0. In an exemplary configuration the refractive index of a nanostructure 220 may be greater than the refractive index of the substrate 202 of the metalens 200.

[0051] In some aspects, a nanostructure 220 may have an encapsulation layer configured to enhance the capabilities of the nanostructure in terms of imposing the phase change onto the incident light. The encapsulation layer may cover the nanostructure 220, e.g. totally or at least partially, e.g. along the height of the nanostructure 220. The encapsulation layer may be configured to cause a scattering of (input) light incident onto the encapsulation layer to provide (output) light with a phase shift with respect to the incident (input) light.

[0052] As discussed in relation to FIG.1B a nanostructure 220 may be configured to provide a respective phase change by tailoring one or more of its properties, e.g. one or more of its geometrical properties in combination with the material properties. For example, a characterization may be carried out to identify the phase change provided by varying the height 224 and/or the width 222 (e.g., the diameter) of a nanostructure 220 for a given material (or material combination) and a given shape of the nanostructure 220. The parameter scan may allow mapping the height 224 and/or the width 222 of the nanostructure 220 (with a certain material, and a certain shape) to corresponding phase changes, as known in the art.

[0053] The present disclosure may be based on the realization that a nanostructure 220 (and correspondingly the plurality of nanostructures 204 in a region 206) may be characterized to identify the phase change that the nanostructure provides for light impinging at different angles of incidence, i.e. not only the normal angle of incidence but also other angles of incidence. The proposed approach may thus include mapping the properties of a nanostructure (e.g., width, height, etc.) to a corresponding phase change and also to a corresponding angle of incidence of incoming light to then enable a corresponding disposition of the nanostructures in respective regions of the metalens.

[0054] Going back to FIG.2A, the nanostructures 204 in each region 206 may thus be configured to provide the respective phase change (according to the target phase profile defining the optical function) having been characterized for light incident at the angle of incidence for that region. By way of illustration, the nanostructures 204 in each region 206 may diffract a maximum amount of light in the first diffraction order for light arriving onto the region 206 at the corresponding angle of incidence. Thus, the first nanostructures 206-1 may diffract a maximum amount of light in the first diffraction order for light arriving onto the first region 206-1 at the first angle of incidence 210-1, the second nanostructures 206-2 may diffract a maximum amount of light in the first diffraction order for light arriving onto the second region 206-2 at the first angle of incidence 210-2, etc.

[0055] Stated in a different fashion, each nanostructure 204 may be configured to provide a nominal phase change when light impinges onto the nanostructure 204 at the angle of incidence for which the nanostructure 204 has been characterized. When light is incident at a different angle, the nanostructure 204 may still provide a phase change that however may deviate from the nominal phase change, thus slightly deteriorating the optical function of the metalens. The “nominal phase change” may correspond to the phase change that the nanostructure 204 has been characterized/designed to provide. In the exemplary configuration in FIG.2A, the first nanostructures 204-1 may induce a first nominal phase change to light impinging at the first angle of incidence 210-1, the second nanostructures 204-2 may induce a second nominal phase change to light impinging at the second angle of incidence 210-2, etc.

[0056] In a preferred configuration (see also FIG.2C), the parameter of choice to configure the plurality of nanostructures 204 in a region 206 according to a respective angle of incidence may be a spacing between (adjacent) nanostructures 204 within the region. Illustratively, the plurality of nanostructures 204 in each region may be characterized by varying the (average) spacing between nanostructures in the region to provide the target phase change and phase profile in the region for the corresponding angle of incidence. The spacing has been found to provide a suitable parameter to implement the strategy proposed herein in a simple, yet efficient manner. It is however understood that in principle also other parameters may be varied among the regions 206 of the metalens 220.

[0057] A region 206 may thus be understood as a continuous portion of the surface 208a of the metalens 202 within which the nanostructures 204 are configured/characterized to provide a (nominal) phase change to incoming light according to the target phase profile and according to the respective angle of incidence. In some aspects, a region 206 may be a continuous portion of the surface 208a of the metalens 202 within which the nanostructures 204 have a respective average spacing between adjacent nanostructures (illustratively, a spacing within a respective range).

[0058] The characterization of the nanostructures 204 may thus take into account the combined effect that the plurality of nanostructures 204 in a region 206 have in manipulating the wavefront. The nanostructures 204 in each region 206 may thus be configured to define a corresponding phase change according to the target phase profile for the metalens 220, and may additionally have an adapted spacing selected according to the expected angle of incidence of light in that region 206.

[0059] **FIG.2C** shows the regions 206-1, 206-2, 206-3 of the metalens 220 in which the nanostructures 204-1, 204-2, 204-3 are disposed with a different spacing between adjacent nanostructures.

[0060] The nanostructures 204 in a region 206 may be disposed according to a periodic arrangement or a non-periodic arrangement. In an exemplary configuration, the nanostructures 204 in a region 206 may form a periodic array of nanostructures 204, e.g. a two-dimensional periodic array. In this configuration, the spacing between adjacent nanostructures 204 may be a period of the array. The array period may describe a distance (e.g., a center-to-center) distance between adjacent nanostructures within the array. For example, the array period may be the same in all directions within the plane defined by the substrate 202, e.g. defined by the surface 208a of the substrate 202. As another example, the array period may have a first value in a first direction in the plane and may have a second value in a second direction in the plane, e.g. a second direction perpendicular to the first direction in the plane.

[0061] In the configuration with a periodic array of nanostructures 204, the plurality of first nanostructures 204-1 may thus form a first (two-dimensional) array with a first array period 226-1 according to the first angle of incidence 210-1, the plurality of second nanostructures 204-2 may form a second (two-dimensional) array with a second array period 226-2 according to the second angle of incidence 210-2, etc. In general, in this configuration each region 206 may include a corresponding array of nanostructures 206 with a unique array period, illustratively with an array period that is different from the array periods of all the other arrays in the other regions. Considering the scenario in which the array period is the same in all directions within the plane, each region 206 may have a unique value for the array period. Considering the scenario in which the array period varies for different directions within the plane, each region 206 may have a unique first value for the array period in a first direction and a unique second value for the array period in a second direction (and optionally, further unique values in other directions).

[0062] The approach proposed herein may be applicable also to a non-periodic arrangement of the nanostructures 204, e.g. to a disposition of the nanostructures 204 with some randomization and corresponding variation in the spacing. In this scenario, reference may be made to an average spacing within the region 206. An average spacing may be understood as an average of the values for the spacing between adjacent nanostructures 204 within the region. In general, references to a “spacing” in the present description may refer to an “average spacing” of a corresponding region of nanostructures.

[0063] In the configuration with a non-periodic arrangement of nanostructures 204, the plurality of first nanostructures 204-1 may thus form a first (non-periodic) array with a first average spacing 226-1 according to the first angle of incidence 210-1, the plurality of second nanostructures 204-2 may form a second (non-periodic) array with a second average spacing 226-2 according to the second angle of incidence 210-2, etc. In general, in this configuration each region 206 may include a corresponding array of nanostructures 206 with a unique average spacing, illustratively with an average spacing that is different from the average spacing of all the other arrays in the other regions 206. Considering the scenario in which the average spacing is the same in all directions within the plane, each region 206 may have a unique value for the average spacing. Considering the scenario in which the average spacing varies for different directions within the plane, each region 206 may have a unique first value for the average spacing in a first direction and a unique second value for the average spacing in a second direction (and optionally, further unique values in other directions).

[0064] In general, it has been found that the spacing (or array period) may be have an inverse relation with the expected angle of incidence in the region. Illustratively, adapting the nanostructures 204 of a region 206 to the corresponding angle of incidence may include selecting a smaller spacing (e.g., with respect to a reference spacing) if a greater angle of incidence (e.g., with respect to a reference angle, e.g. 0°) is expected in that region.

[0065] With reference to the exemplary configuration in FIG.2A, the first angle of incidence 210-1 may be smaller than the second angle of incidence 210-2, and, accordingly, a first (average) spacing (e.g., a first array period) 226-1 of the first nanostructures 204-1 may be greater than a second (average) spacing (e.g., a second array period) 226-2 of the second nanostructures 204-2. For example, the first angle of incidence 210-1 may correspond to the normal direction, e.g. may be 0°, and the second angle of incidence 210-2 may correspond to a direction tilted with respect to the normal direction. In a corresponding manner, the second angle of incidence 210-2 may be smaller than the third angle of incidence 210-3, and, accordingly, the second (average) spacing 226-2 of the second nanostructures 204-2 may be greater than a third (average) spacing (e.g., a third array period) 226-3 of the third nanostructures 204-3, etc.

[0066] In general, the light incident on a region 206 may have an angle of incidence within a corresponding range of angles. The range of angles may be centered around the angle of incidence considered for that region in the characterization (e.g., the first angle of incidence 210-1, the second angle of incidence 210-2, etc.). Illustratively, in view of the spatial extension of a region 206, light may impinge at different locations within the region at angles of incidence that differ slightly from the "central" angle of incidence. Reference herein to the "angle of incidence" associated with a region 206 may thus be understood, in some aspects, to describe an angle of incidence in a corresponding range for that region, or to the angle of incidence around which the range is centered.

[0067] The angular extension of the range may vary depending on the number of regions into which the metalens 200 is subdivided, e.g. according to a compromise between a granularity of the light manipulation and a complexity of the fabrication process. As a numerical example, the range of angles of incidence associated with a region 206 may have an extension of about 5° (e.g., ±2.5° around a selected angle of incidence), e.g. an extension of about 10° (e.g., ±5°).

[0068] Depending on the disposition of the regions 206 on the metasurface 208a (see also FIG.2D and FIG.2E), there may be a relationship between the spacing (e.g., array period) within a region and a distance of that region from the center of the metalens 220. Illustratively, during an operation of the metalens 220 it may be expected that a region 206 in a certain position will receive light at a certain angle, another region 206 in another position will receive light at another angle, etc.

[0069] In general, it may be expected that a central region 206 of the metalens 220 (e.g., the first region 206-1 in this example) will receive light having light rays parallel to the normal to the surface 208a, 208b, while regions 206 farther away from the center of the metalens 220 will receive light at increasing angles of incidence. The average spacing (e.g., array period) of the nanostructures 204 in a region 206 may thus be inversely related to a distance of the region 206 from the geometrical center of the metasurface 208a. The distance between a region 206 and the center of the metasurface 208a may be defined in any suitable manner, e.g. as a distance between a geometrical center of the region 206 and the center of the metasurface 208a, as a distance between a border of the region and the center of the metasurface 208a, and the like.

[0070] Considering the exemplary configuration in FIG.2A to FIG.2C, the first region 206-1 may be at a first distance from the geometrical center of the metasurface 208a, the second region 206-2 may be at a second distance from the geometrical center of the metasurface 208a, the third region 206-3 may be at a third distance from the geometrical center of the metasurface 208a, etc. In this exemplary scenario, the first distance may be less than the second distance, so that the first spacing 226-1 may be greater than the second spacing 226-2. The second distance may be less than the third distance, so that the second spacing 226-2 may be greater than the third spacing 226-3, etc.

[0071] The value of the spacing between adjacent nanostructures 204 in the metasurface may be selected according to the desired phase change profile for the metalens, and taking into consideration the angles of incidence, as discussed above. As a numerical example, the spacing between adjacent nanostructures 204 may be in the range from 50 nm to 1000 nm, e.g. in the range from 100 nm to 700 nm, e.g. in the range from 200 nm to 500 nm.

[0072] In principle, the nanostructures 204 in different regions 206 may have properties adapted according to the target phase profile, and according to the expected angle of incidence. For example, the nanostructures 204 in different regions 206 may include or may be made of the same material, and may have different geometrical properties, e.g. a different height, a different width, a different radius, etc. As another example, nanostructures 204 in different regions 206 may have same geometrical properties and may include or may be made of different materials (e.g., materials with different refractive index). As a further example, nanostructures 204 in different regions 206 may have same geometrical properties and may include or may be made of the same material, and may have a different encapsulation layer (e.g., with a different encapsulation material having different refractive properties).

[0073] As discussed above, the nanostructures 204 in each region 206 may provide a phase change according to the target phase profile for the metalens 200. For example, a first nanostructure 204-1 may be configured to induce a first phase change to incident light, a second nanostructure 204-2 may be configured to induce a second phase change to incident light, a third nanostructure 204-3 may be configured to induce a third phase change to incident light, etc. Depending on the target phase profile, the first phase change may be different from the second phase change or may be the same as the second phase change. In a corresponding manner, the second phase change may be different from the third phase change or may be the same as the third phase change. It is also understood that some of the first nanostructures 204-1 may provide the same phase change as some of the second nanostructures 204-2, and a different phase change with respect to other second nanostructures 204-2, etc.

[0074] In principle, the regions 206 may be disposed according to any suitable configuration within the metasurface 208a, e.g. depending on an intended operation of the metalens 200, e.g. depending on the expected angles of incidence of incoming light during the operation of the metalens 200. **FIG.2D** and **FIG.2E** illustrate two possible dispositions for the regions 206, but it is understood that also other configurations may be provided. Furthermore, a region 206 may have any suitable shape, e.g. any suitable perimeter or contour, depending on the desired configuration for the metalens 200, the target phase profile, the expected angles of incidence, etc. In FIG.2D and FIG.2E regions 206 having a circular shape, ring shape, and rectangular shape are illustrated, but it is understood that a region may have in principle any suitable shape. A region 206 may have a regular or irregular shape, as other examples a region may have a square shape, an elliptical shape, a triangular shape, a pentagonal shape, a hexagonal shape, etc.

[0075] In a preferred configuration 250d, which may provide a symmetric light manipulation, the regions 206 configured according to different angles of incidence may be disposed in a concentric manner from a geometrical center of the metasurface 208a. Illustratively, in this configuration, the first region 206-1 may be a central region of the metasurface 208a and may be a circular region. The other regions 206-2, 206-3 may be disposed in a concentric manner around the first region 206-1. In an exemplary configuration, the nanostructures 204 within each region 206 may be disposed with a circular symmetry with respect to the geometric center of the metasurface 208a.

[0076] The second region 206-2 and the third region 206-3 (and further regions, if present) may be configured as ring-shaped regions (illustratively, annular regions) disposed around the first region 206-1. In this scenario, the second region 206-2 may be disposed to surround the first region 206-1, the third region 206-3 may be disposed to surround the second region 206-2, etc. Illustratively, the first region 206-1 may be a (substantially) circular region disposed around the center of the metasurface 208a, and the other regions 206-2, 206-3 may be disposed concentrically around the first region 206-1. In this configuration, the distance of a region 206 from the center of the metasurface 208a may be understood as a radius, e.g. a first radius between the second region 206-2 and the center, a second radius between the third region 206-3 and the center, etc.

[0077] In another exemplary configuration 250e, the regions 206 may be disposed adjacent to one another. Illustratively, the second region 206-2 may be disposed adjacent to the first region 206-1, e.g. in a first direction in the plane of the substrate 202. The third region 206-3 may be disposed adjacent to the second region 206-2, etc. By way of illustration, in the exemplary configuration 250e, the regions 206 may be disposed according to a stripe pattern, in which each region 206 corresponds to a respective stripe, e.g. to a respective coordinate (or range of coordinates) along the first direction in the plane of the substrate 202 (e.g., a horizontal direction).

[0078] In an exemplary configuration, as shown in FIG.2E, a symmetric disposition with respect to the center of the metasurface 208a may be provided also in this case. For example, the first region 206-1 may be a central region of the metasurface 208a. The metalens may further include two second regions 206-2 disposed at the two sides of the first region 206-1 (along the first direction). Illustratively, nanostructures 204-2 configured according to the second angle of incidence may be disposed at the two sides of the first region 206-1 in two non-connected second regions 206-2. The metalens may further include two third regions 206-3 each disposed adjacent to a respective second region 206-2, etc. In this scenario, the average spacing (e.g., array period) may be unique to all regions of the same type, illustratively to all regions configured according to the same angle of incidence or same range for the angle of incidence.

[0079] In principle, the configuration of a metalens as described herein may be adapted in any suitable manner depending on the conditions expected during an operation of the metalens. In a preferred configuration, the metalens may be combined with an optical element to ensure that the different regions of the metalens are illuminated with light at the angle of incidence for which that region has been characterized and configured. This arrangement may allow to fully exploit the adapted configuration of the proposed metalens, and thus to achieve an improved efficiency for the light manipulation.

[0080] **FIG.3** shows an optical system 300 including a metalens 200 configured as described herein, and an optical element 302 configured to direct light towards the metalens 200 at a plurality of different angles.

[0081] The optical element 302 may be configured to receive input light 304 and diffract the input light 304 to provide output light 306 at a plurality of output angles. Illustratively, the optical element 302 may be configured to diffract the input light 304 so that the light rays at the output side propagate (towards the metalens 200) at a plurality of different angles, thus impinging onto the metalens 200 at difference angles of incidence. By way of illustration, the optical element 302 may be configured to spread the input light 304 so that at the output side the output light 306 travels in different directions corresponding to different output angles (and, accordingly, different angles of incidence).

[0082] In the optical system 300, the optical element 302 and the metalens 200 may be disposed such that the different regions 206 of the metalens 200 receive light output from the optical element 302 at the angle of incidence for which the region has been characterized/configured. Illustratively, the optical element 302 and the metalens 200 may be configured such that the output light 306 impinges on the metalens 200 at a different angle of incidence in each region 206. Considering the exemplary configuration in FIG.2A, the optical element 302 and the metalens 200 may be configured such that the first region 206-1 receives output light 306 at the first angle of incidence, the second region 206-2 receives output light 306 at the second angle of incidence, etc.

[0083] Stated in a different fashion, the optical element 302 may cause light diffraction to spread light over a plurality of propagation angles, and the metalens 200 may be disposed with respect to the optical element 302 in such a way that the light propagating at a certain propagation angle arrives on the surface 208a at a corresponding angle of incidence in the corresponding region 206 of the metalens 200. The relative arrangement of the metalens 200 with respect to the optical element 302 may thus be adapted according to a known diffraction pattern at the output of the optical element 302 and according to the subdivision of the metalens 200 into regions 206.

[0084] As mentioned in relation to FIG.2A, the angles of incidence of light illuminating a certain region may vary slightly within a certain (limited) angular range. In this regard, the optical element 302 and the metalens 200 may be configured such that each region 206 receives output light 306 having an angle of incidence within a corresponding angular range for that region 206, e.g. an angular range centered around the angle of incidence for which that region was characterized/designed. The “acceptance angle” of a region 206 may thus vary based on the number of regions 206 into which the metalens 200 is subdivided, e.g. may increase for decreasing number of regions 206 (and thus decreasing granularity in the adaptation of the metalens).

[0085] Considering the exemplary configuration shown in the figures, the optical element 302 and the metalens 200 may be configured (e.g., disposed with respect to one another) such that the first region 206-1 receives output light at a first range of angles of incidence (e.g., centered around the first angle of incidence 210-1), the second region 206-2 receives output light at a second range of angles of incidence (e.g., centered around the second angle of incidence 210-2), etc.

[0086] The optical element 302 may have any suitable configuration to provide diffraction of light. In a simple configuration the optical element 302 may include an aperture, e.g. a circular aperture or an aperture with any other suitable shape. The aperture may have a dimension suitable to provide diffraction in the wavelength range of interest. The dimension of the aperture (e.g., its radius) may be adapted to increase/decrease the amount of diffraction (illustratively, the tilting of the light at the output) depending on the overall configuration of the optical system 300, e.g. the disposition of the regions 206 in the metalens 200, the disposition of the metalens 200 with respect to the aperture, etc.

[0087] In this configuration the optical element 302 may thus be configured to partially block light and to partially allow light to pass through the aperture (during an operation of the optical system 300). The input light 304 may pass through the aperture (illustratively, an opening) and may spread into the plurality of output angles. In this configuration, the optical element 302 may include or may be made of a material that is opaque (or non-transmissive) for light in the wavelength range of interest, and may have the aperture to let light to pass through at the aperture.

[0088] The use of an aperture may provide a simple configuration to achieve the desired distribution of light incident on the metalens 200. It is however understood that in principle the optical element 302 may also have another (e.g., more complex) configuration to achieve the diffraction of light and distribute light over a plurality of output angles. As another example, the optical element 302 may include a diffractive optical element configured to deflect the input light 304 at a plurality of output angles (e.g., deflection angles). As a further example, the optical element 302 may itself be a metalens configured to diffract the input light 304 into the plurality of output angles. It is also understood that other intervening elements may be disposed between the optical element 302 and the metalens 200 to direct the light towards the metasurface 208a, e.g. one or more mirrors, one or more lenses, etc.

[0089] In the configuration in FIG.3, the metalens 200 may be disposed with respect to the optical element 302 such that the metasurface 208a with the plurality of regions faces away from the optical element 302 (and the other surface 208b faces the optical element). This configuration may provide a greater angle of acceptance for the manipulation of light at the metalens 200. It is however understood that in principle also the opposite configuration may be provided in which the metasurface 208a of the metalens 200 faces the optical element 302 from which light comes.

[0090] In the exemplary configuration in FIG.3 the metalens 200 may be configured to focus light onto an image sensor 102. Illustratively, the nanostructures 204 may defined a phase profile on the metasurface 208a that causes focusing of the light 304, 306 onto an active area of the image sensor 102. In this scenario the input light 304 may be light from the field of view of an imaging device (e.g., the imaging device 100 in FIG.1A), e.g. to implement tracking or other suitable applications. It is however understood that the aspects described in relation to the optical system 300 may apply in a corresponding manner to other possible applications of the metalens 200, e.g. for collimating light, diverging light, etc.

[0091] For example, considering light emission, the input light 304 may be light from a light source, e.g. part of the optical system 300. The light source may emit light which is then manipulated by the metalens according to a desired emission profile. As an example, the light source may emit collimated light and the optical element 302 may diffract the collimated light into the plurality of propagation angles. In another configuration, the light source itself may be configured to emit light at a plurality of emission angles towards the metalens 200 so that each region 206 receives light emitted at a respective emission angle corresponding to the respective angle of incidence for that region.

[0092] Considering light detection, the light 304, 306 received at the metalens 200 may be probing light emitted by a probing system (e.g., by a light emission system of the imaging device 100). In this scenario, the light received at the metalens 200 may be a back-reflection of light emitted into the field of illumination/field of view of the image sensor 102 or imaging device. As discussed in relation to FIG.2A, the nanostructures of the metalens 200 may be configured according to the wavelength range of interest, e.g. according to the wavelength of the emitted light for light emission and/or detection.

[0093] **FIG.4** shows a schematic flow diagram of a method 400 of fabricating a metalens, e.g. the metalens 200, according to the various aspects. In general, the method 400 may include a characterization phase 410 and a fabrication phase 420.

[0094] The method 400 may include, in the characterization phase 410, characterizing (e.g., simulating, estimating) a phase change induced by a nanostructure to light incident on the nanostructure at a predefined angle of incidence. The predefined angle of incidence may be within a range of angles of incidence that the light arriving onto the metalens is expected to have during an operation of the metalens. The predefined angle of incidence may thus be the normal angle of incidence or any other angle different from the normal angle of incidence (illustratively, any other angle greater than 0° and less than 90°).

[0095] The characterization 410 may thus include identifying a correspondence between the properties of the nanostructure (e.g., the geometrical properties, material properties, etc.) and the corresponding phase change for a certain angle of incidence of incoming light. The characterization 410 thus include mapping the properties of a nanostructure to a corresponding phase change and a corresponding angle of incidence of light incident on the nanostructure. The characterization allows thus creating a library identifying which nanostructure provides the desired properties in terms of phase change (to provide a target phase profile) and angle of incidence (to define where to dispose the nanostructure).

[0096] The method 400 may further include, in the fabrication phase 420, forming a plurality of nanostructures on a surface of the metalens according to a target phase profile. Illustratively, the method 400 may include forming the nanostructure on a substrate of the metalens with properties that provide the phase change suitable to achieve the target phase profile, as indicated by the characterization 410. The target phase profile may be a distribution of phase shifts over the surface of the metalens to implement a predefined optical function, e.g. focusing, collimation, and the like.

[0097] In addition to forming/disposing the nanostructures according to the target phase profile, the method 400 may include forming/disposing the nanostructures in a plurality of regions, each corresponding to a respective angle of incidence of light impinging on the metalens. Illustratively, each nanostructure may be characterized to identify a corresponding phase change for a certain angle of incidence, and the method 400 may include forming/disposing each nanostructure in a region corresponding to the angle of incidence used for the characterization of the nanostructure (illustratively, the angle of incidence used to determine the properties of the nanostructure to achieve that phase change).

[0098] The strategy proposed herein has been characterized via simulations. The optical efficiency of a metalens subdivided into a plurality of zones have been compared with a metalens in which the nanostructures had been characterized/configured without considering the angle of incidence of incoming light. For example, considering an angle of incidence of 20°, a metalens in which the nanostructures in the region receiving light at that angle of incidence are adapted as discussed herein (e.g., with a smaller average spacing) showed an improvement in the efficiency of the first diffraction order. Analogous results were obtained for an angle of incidence of 30°.

[0099] In conclusion, a metalens as proposed herein includes zones adapted to different angles of incidence of incoming light, and the properties of the nanostructures are tailored to increase the efficiency of the nanostructures for light coming at the expected angle of incidence. The proposed metalens may thus enhance the efficiency of light manipulation to implement a desired optical function compared to a conventional design in which the nanostructures are configured/disposed without taking into consideration the actual operating conditions of the metalens.

[00100] The following examples pertain to aspects of the present disclosure.

[00101] Example 1 is a metalens including: a metasurface with a plurality of regions, wherein the plurality of regions include, at least: a first region with a plurality of first nanostructures configured in accordance with a first angle of incidence of light arriving on the metasurface; and a second region with a plurality of second nanostructures configured in accordance with a second angle of incidence of light arriving on the metasurface.

[00102] In Example 2, the metalens according to example 1 may optionally further include that the first nanostructures are configured such that the first nanostructures diffract a maximum amount of light in the first diffraction order for light arriving onto the first region at the first angle of incidence; and that the second nanostructures are configured such that the second nanostructures diffract a maximum amount of light in the first diffraction order for light arriving onto the second region at the second angle of incidence.

[00103] In Example 3, the metalens according to example 1 or 2 may optionally further include that the first nanostructures have a first average spacing between adjacent first nanostructures; that the second nanostructures have a second average spacing between adjacent second nanostructures; and that the first average spacing is different from the second average spacing.

[00104] In Example 4, the metalens according to example 3 may optionally further include that the first angle of incidence is less than the second angle of incidence; and that the first average spacing is greater than the second average spacing.

[00105] In Example 5, the metalens according to any one of examples 1 to 4 may optionally further include that the first region is at a first distance from the geometric center of the metasurface; that the second region is at a second distance from the geometric center of the metasurface; and that the first distance is less than the second distance.

[00106] In Example 6, the metalens according to any one of examples 1 to 5 may optionally further include that the first region is a substantially circular region centered around the geometric center of the metasurface, and that the second region is a substantially ring-shaped region disposed to surround the first region.

[00107] In Example 7, the metalens according to any one of examples 1 to 6 may optionally further include that the plurality of regions further include a third region with a plurality of third nanostructures configured in accordance with a third angle of incidence of light arriving on the metasurface.

[00108] Example 8 is an optical system including: a metalens according to anyone of examples 1 to 7; and an optical element configured to receive input light and diffract the input light into output light at a plurality of output angles, wherein the optical element and the metalens are disposed such that the first region of the metasurface receives output light at the first angle of incidence, and the second region of the metasurface receives output light at the second angle of incidence.

[00109] In Example 9, the optical system according to example 8 may optionally further include that the metalens includes a substrate with a first surface and a second surface, that the second surface of the substrate faces the optical element and the first surface of the substrate faces away from the optical element, and that the metasurface is disposed on the first surface of the substrate.

[00110] Example 10 is a metalens including: a metasurface with a plurality of regions, wherein each region includes a plurality of nanostructures configured to impose a phase change to light incident on the nanostructures; wherein each region has an average spacing between adjacent nanostructures within the region, and wherein the average spacing of each region is unique to that region among the average spacings of the plurality of regions.

[00111] The term "processor" (or processing circuit) as used herein may be understood as any kind of technological entity that allows handling of data. The data may be handled according to one or more specific functions that the control circuit may execute. Further, a control circuit as used herein may be understood as any kind of circuit, e.g., any kind of analog or digital circuit. A control circuit may thus be or include an analog circuit, digital circuit, mixed-signal circuit, logic circuit (e.g., a hard-wired logic circuit or a programmable logic circuit), microprocessor, Central Processing Unit (CPU), Graphics Processing Unit (GPU), Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA), integrated circuit, Application Specific Integrated Circuit (ASIC), etc., or any combination thereof.

[00112] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration”. Any embodiment or design described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[00113] The phrase “at least one” and “one or more” may be understood to include a numerical quantity greater than or equal to one (e.g., one, two, three, four, [...], etc.). The phrase “at least one of” with regard to a group of elements may be used herein to mean at least one element from the group consisting of the elements. For example, the phrase “at least one of” with regard to a group of elements may be used herein to mean a selection of: one of the listed elements, a plurality of one of the listed elements, a plurality of individual listed elements, or a plurality of a multiple of individual listed elements.

[00114] While the invention has been particularly shown and described with reference to specific aspects, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes, which come within the meaning and range of equivalency of the claims, are therefore intended to be embraced.

List of reference signs

100	Imaging device
102	Image sensor
104	Optical module
106	Processor
108	Metalens
110	Field of view
150	Metalens
152	Substrate
154	Nanostructures
200	Metalens
202	Substrate
204	Nanostructures
204-1	First nanostructures
204-2	Second nanostructures
204-3	Third nanostructures
206	Regions
206-1	First region
206-2	Second region
206-3	Third region
208a	First surface
208b	Second surface
210-1	First angle of incidence
210-2	Second angle of incidence
210-3	Third angle of incidence
220	Nanostructure
222	First lateral dimension
224	Second lateral dimension
226-1	First spacing
226-2	Second spacing
226-3	Third spacing
250d	Disposition of the regions
250e	Disposition of the regions
300	Optical system
302	Optical element
304	Input light
306	Output light
400	Method
410	Method step
420	Method step

Claims

1. A metalens (200) comprising:

a metasurface (208a) with a plurality of regions (206),

wherein the plurality of regions (206) comprise, at least:

a first region (206-1) with a plurality of first nanostructures (204-1) configured in accordance with a first angle of incidence (210-1) of light arriving on the metasurface (208a) such that the first nanostructures diffract a maximum amount of light in the first diffraction order for light arriving onto the first region (206-1) at the first angle of incidence (210-1); and

a second region (206-2) with a plurality of second nanostructures (204-2) configured in accordance with a second angle of incidence (210-2) of light arriving on the metasurface (208a) such that the second nanostructures (204-2) diffract a maximum amount of light in the first diffraction order for light arriving onto the second region (206-2) at the second angle of incidence (210-2).

2. The metalens (200) according to claim 1,

wherein the first nanostructures (204-1) have a first average spacing (226-1) between adjacent first nanostructures (204-1);

wherein the second nanostructures (204-2) have a second average spacing (226-2) between adjacent second nanostructures (204-2); and

wherein the first average spacing (226-1) is different from the second average spacing (226-2).

3. The metalens (200) according to claim 2,

wherein the first angle of incidence is less than the second angle of incidence; and

wherein the first average spacing (226-1) is greater than the second average spacing (226-2).

4. The metalens (200) according to claim 2 or 3,

wherein the first average spacing (226-1) is a first center-to-center distance between adjacent first nanostructures (204-1); and

wherein the second average spacing (226-2) is a second center-to-center distance between adjacent second nanostructures (204-2).

5. The metalens (200) according to anyone of claims 2 to 4,

wherein the first nanostructures (204-1) are disposed in a first periodic array and the first average spacing (226-1) is a first array period, and

wherein the second nanostructures (204-2) are disposed in a second periodic array and the second average spacing (226-1) is a second array period.

6. The metalens (200) according to any one of claims 1 to 5,

wherein the first region (206-1) is at a first distance from the geometric center of the metasurface (208a);

wherein the second region (206-2) is at a second distance from the geometric center of the metasurface (208a); and

wherein the first distance is less than the second distance.

7. The metalens (200) according to any one of claims 1 to 6,

wherein the first region (206-1) is a substantially circular region centered around the geometric center of the metasurface (208a), and

wherein the second region (206-2) is a substantially ring-shaped region disposed to surround the first region (206-1).

8. The metalens (200) according to any one of claims 1 to 7,

wherein the plurality of regions (206) further comprise a third region (206-3) with a plurality of third nanostructures (204-3) configured in accordance with a third angle of incidence (210-3) of light arriving on the metasurface (208a) such that the third nanostructures (204-3) diffract a maximum amount of light in the first diffraction order for light arriving onto the third region (206-3) at the third angle of incidence (210-3).

9. The metalens (200) according to claims 7 and 8,

wherein the third region (206-3) is a substantially ring-shaped region disposed to surround the second region (206-2).

10. An optical system (300) comprising:

a metalens (200) according to anyone of claims 1 to 9; and

an optical element (302) configured to receive input light (304) and diffract the input light (304) into output light (306) at a plurality of output angles,

wherein the optical element (302) and the metalens (200) are disposed such that the first region (206-1) of the metasurface (208a) receives output light (306) at the first angle of incidence (210-1), and the second region (206-2) of the metasurface (208a) receives output light (306) at the second angle of incidence (210-2).

11. The optical system (300) according to claim 10,

wherein the metalens comprises a substrate (202) with a first surface (208a) and a second surface (208b),

wherein the second surface (208b) of the substrate (202) faces the optical element (302) and the first surface (208a) of the substrate (202) faces away from the optical element (302), and

wherein the metasurface (208a) is disposed on the first surface (208a) of the substrate (202).

12. The optical system (300) according to claim 10 or 11,

wherein the optical element (302) is or comprises an optical aperture.

13. The optical system (300) according to any one of claims 10 to 12, further comprising:

an image sensor (102),

wherein the metalens (200) is configured to focus light onto the image sensor (102).

14. A metalens (200) comprising:

a metasurface (208a) with a plurality of regions (206),

wherein each region (206) comprises a plurality of nanostructures (204) configured to impose a phase change to light incident on the nanostructures (204);

wherein each region (206) has an average spacing between adjacent nanostructures (204) within the region, and

wherein the average spacing of each region (206) is unique to that region among the average spacings of the plurality of regions (206), such that the nanostructures (204) within each region (206) provide a nominal phase change to light impinging onto the nanostructure (204) at a respective angle of incidence associated with the region (206) and provide a phase change different from the nominal phase change to light impinging onto the nanostructure (204) at an angle different from the respective angle of incidence associated with the region (206).

15. A method (400) of fabricating a metalens, the method comprising:

characterizing (410) a phase change induced by a nanostructure to light incident on the nanostructure at a predefined angle of incidence;

forming (420) a plurality of nanostructures on a surface of a metalens according to a target phase profile, wherein forming (420) the plurality of nanostructures comprises disposing each nanostructure in a respective region of a plurality of regions of the surface of the metalens according to the corresponding angle of incidence used for the characterization of the nanostructure.

FIG.1A

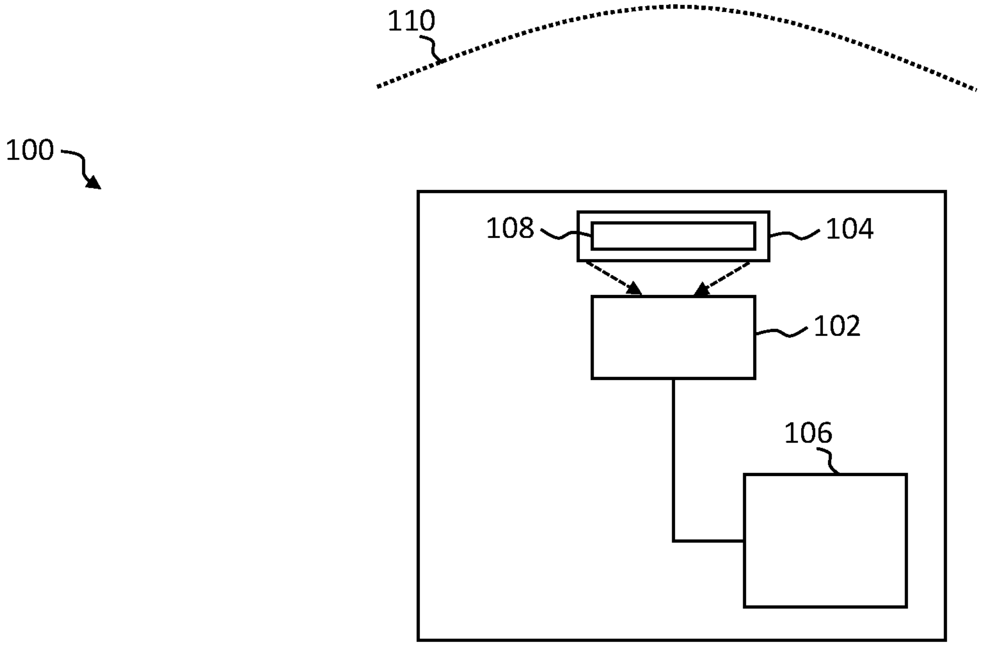


FIG.1B

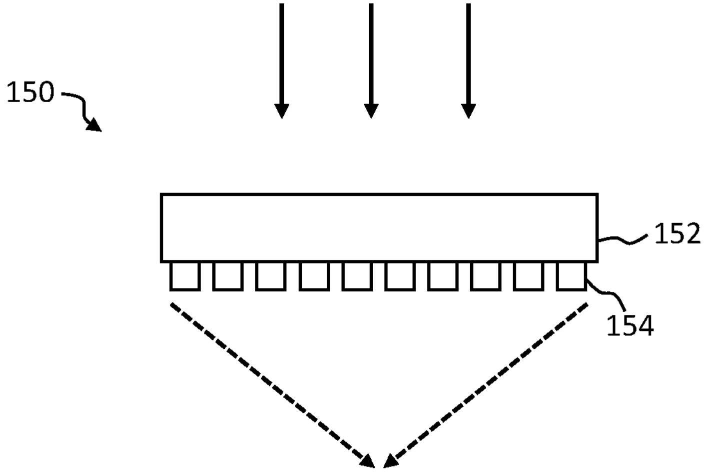


FIG.2A

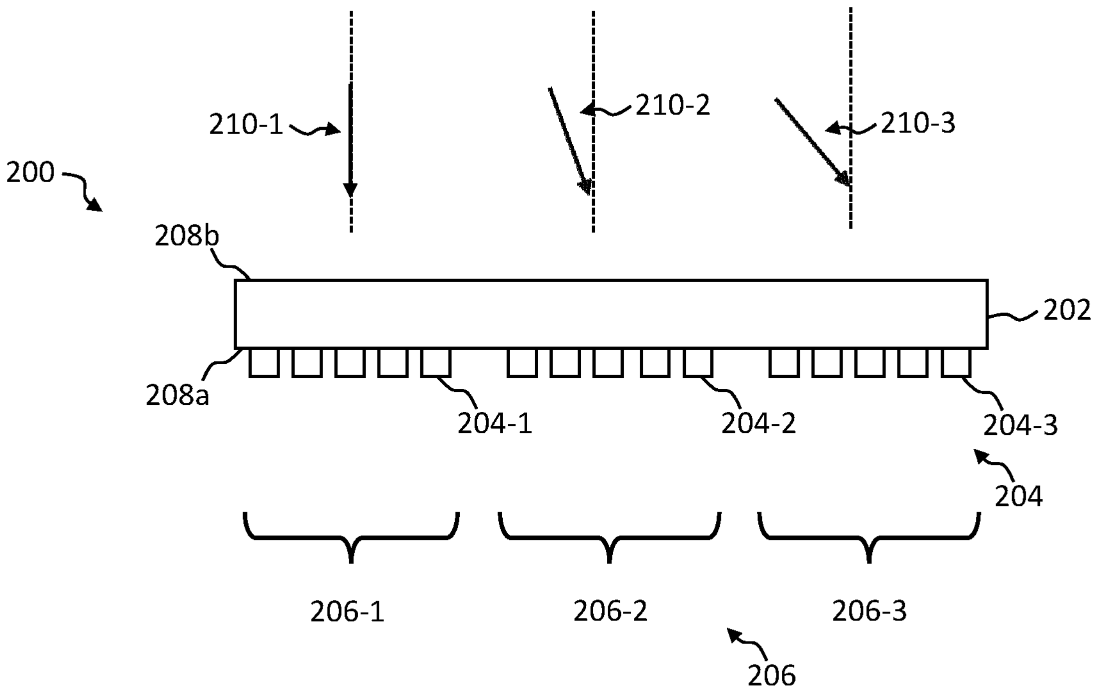

200
210-1
210-2
210-3
208b
202
208a
204-1
204-2
204-3
204
206-1
206-2
206-3
206

FIG.2B

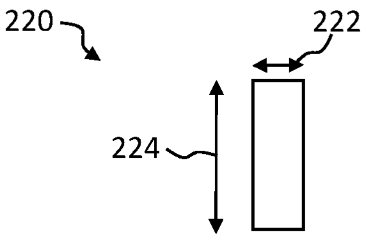

220
222
224

FIG.2C

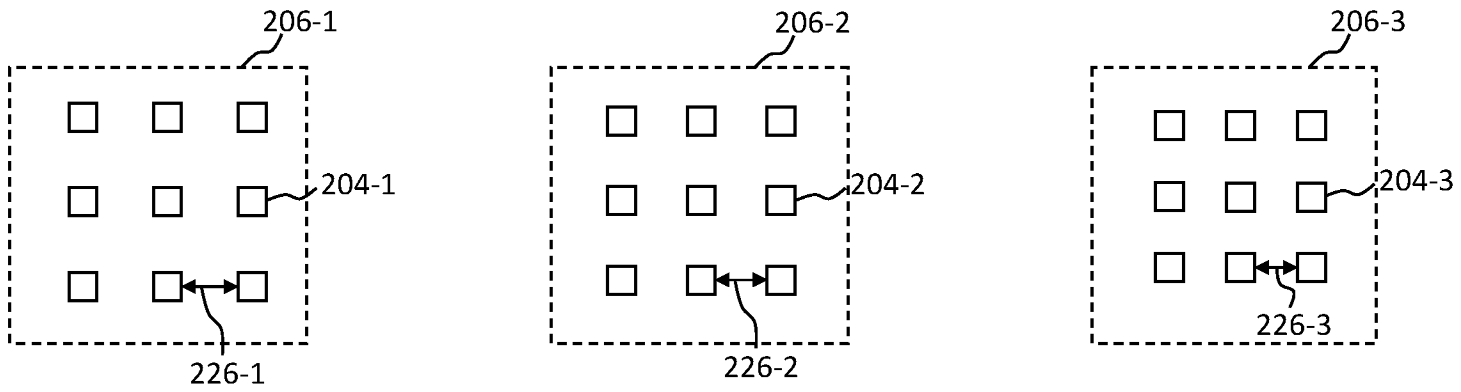


FIG.2E

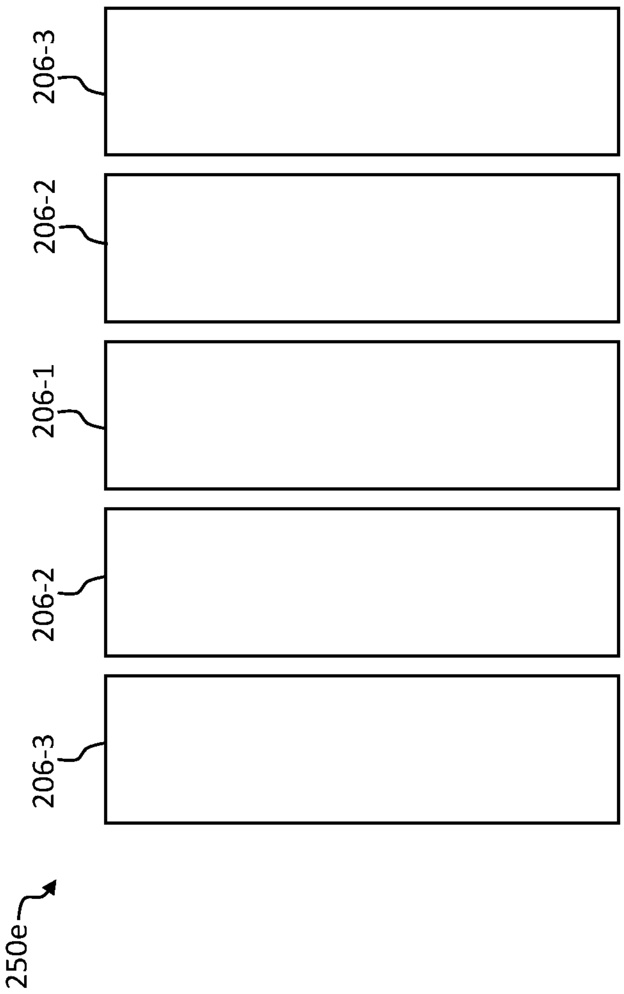


FIG.2D

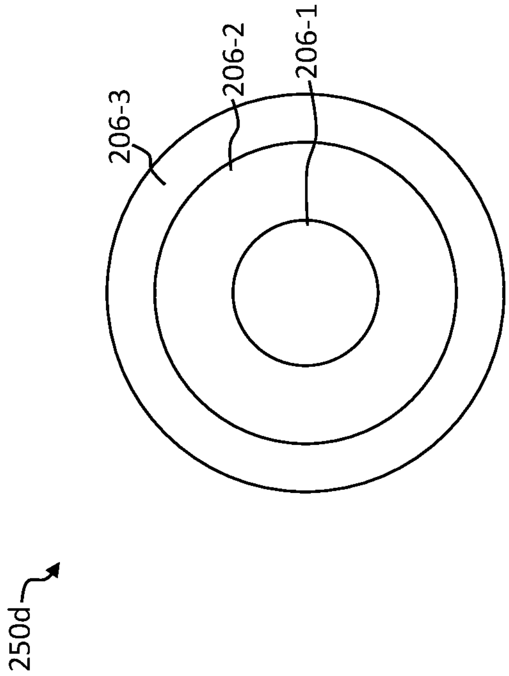
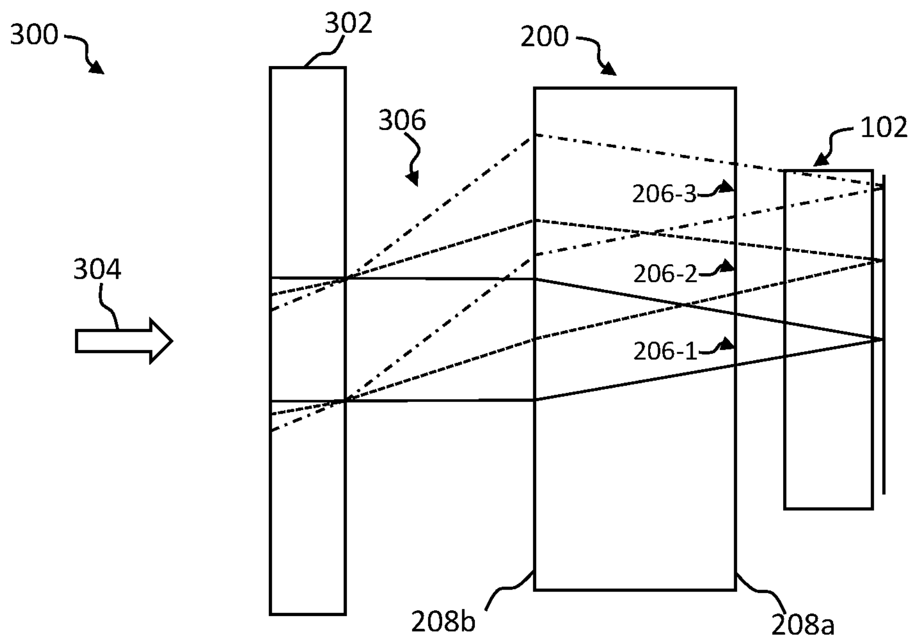


FIG.3



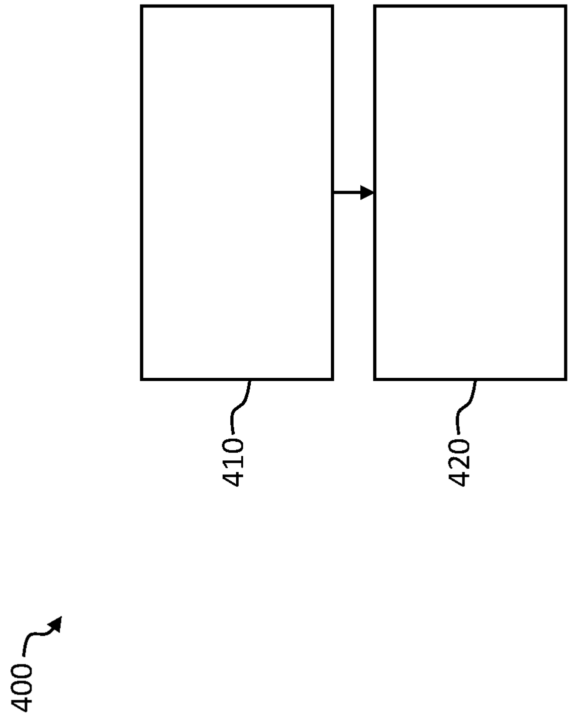


FIG.4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/065897

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B1/00 G02B5/18
ADD.

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)
G02B

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2017/082263 A1 (BYRNES STEVE [US] ET AL) 23 March 2017 (2017-03-23) paragraph [0155] - paragraph [0158]; figures 3B, 8, 9A-9B, 11 -----	1-9,14, 15
X	US 2022/179222 A1 (GUO RUI [CN] ET AL) 9 June 2022 (2022-06-09) paragraph [0048]; figures 7i, 7j -----	1-9,14, 15
X	US 2023/012003 A1 (MA JIAN [US] ET AL) 12 January 2023 (2023-01-12) paragraph [0080] - paragraph [0095]; figures 1A-4 -----	1-15
X	US 2022/276422 A1 (HOUCK WILLIAM D [US]) 1 September 2022 (2022-09-01) figure 1A ----- -/--	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

"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 26 August 2024	Date of mailing of the international search report 04/09/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Braun, P

1

International application No
PCT/EP2024/065897

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2021/044748 A1 (HU JUEJUN [US] ET AL) 11 February 2021 (2021-02-11) paragraph [0061]; figures 1A, 4 -----	1-15

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2024/065897

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2017082263 A1	23-03-2017	CN 108291983 A	17-07-2018
		EP 3353578 A1	01-08-2018
		EP 3825738 A2	26-05-2021
		JP 6748197 B2	26-08-2020
		JP 2018537804 A	20-12-2018
		US 2017082263 A1	23-03-2017
		US 2018274750 A1	27-09-2018
		US 2019137075 A1	09-05-2019
		WO 2017053309 A1	30-03-2017
US 2022179222 A1	09-06-2022	CN 112444968 A	05-03-2021
		EP 4020056 A1	29-06-2022
		US 2022179222 A1	09-06-2022
		WO 2021036525 A1	04-03-2021
US 2023012003 A1	12-01-2023	BR 112023027400 A2	12-03-2024
		CN 117597604 A	23-02-2024
		EP 4367536 A1	15-05-2024
		KR 20240021843 A	19-02-2024
		TW 202309581 A	01-03-2023
		US 2023012003 A1	12-01-2023
US 2022276422 A1	01-09-2022	CN 114659629 A	24-06-2022
		EP 4036615 A1	03-08-2022
		KR 20220091342 A	30-06-2022
		US 11333811 B1	17-05-2022
		US 2022276422 A1	01-09-2022
		US 2024027666 A1	25-01-2024
US 2021044748 A1	11-02-2021	AU 2020324338 A1	03-03-2022
		CA 3146753 A1	11-02-2021
		CN 114341674 A	12-04-2022
		EP 4010742 A1	15-06-2022
		IL 290397 A	01-04-2022
		JP 2022544213 A	17-10-2022
		KR 20220042406 A	05-04-2022
		US 2021044748 A1	11-02-2021
		US 2021306564 A1	30-09-2021
		WO 2021025759 A1	11-02-2021