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(54) **OPTICAL DEVICE, A SYSTEM AND A METHOD FOR FORMING A DISTRIBUTION OF A THREE-DIMENSIONAL LIGHT FIELD**

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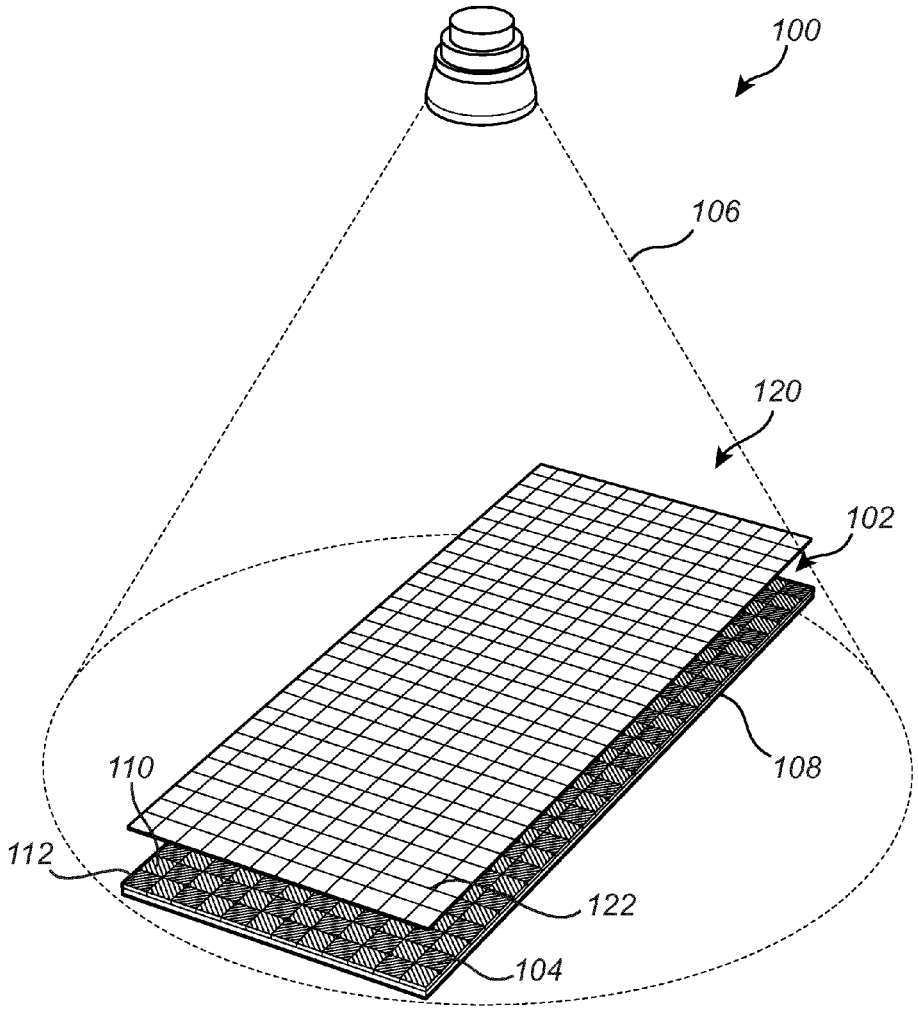
(57) **ABSTRACT**

An optical device (**100**) for forming a distribution of a three-dimensional light field comprises: an array (**102**) of unit cells (**104**), a unit cell (**104**) being individually addressable for switching the optical property of the unit cell (**104**) between a first and a second condition; wherein the unit cells (**104**) are configured to be selectively active or inactive and wherein the array (**102**) comprises at least a first and a second disjoint subset (**110**; **112**; **114**; **116**), and wherein the unit cells (**104**) in a subset (**110**; **112**; **114**; **116**) are configured to be jointly switched from inactive to active, wherein the active unit cells (**104**) are configured to interact with an incident light beam (**106**) for forming the distribution of the three-dimensional light field; and wherein the optical device (**100**) is configured to address inactive unit cells (**104**) for switching the optical property of unit cells (**104**).



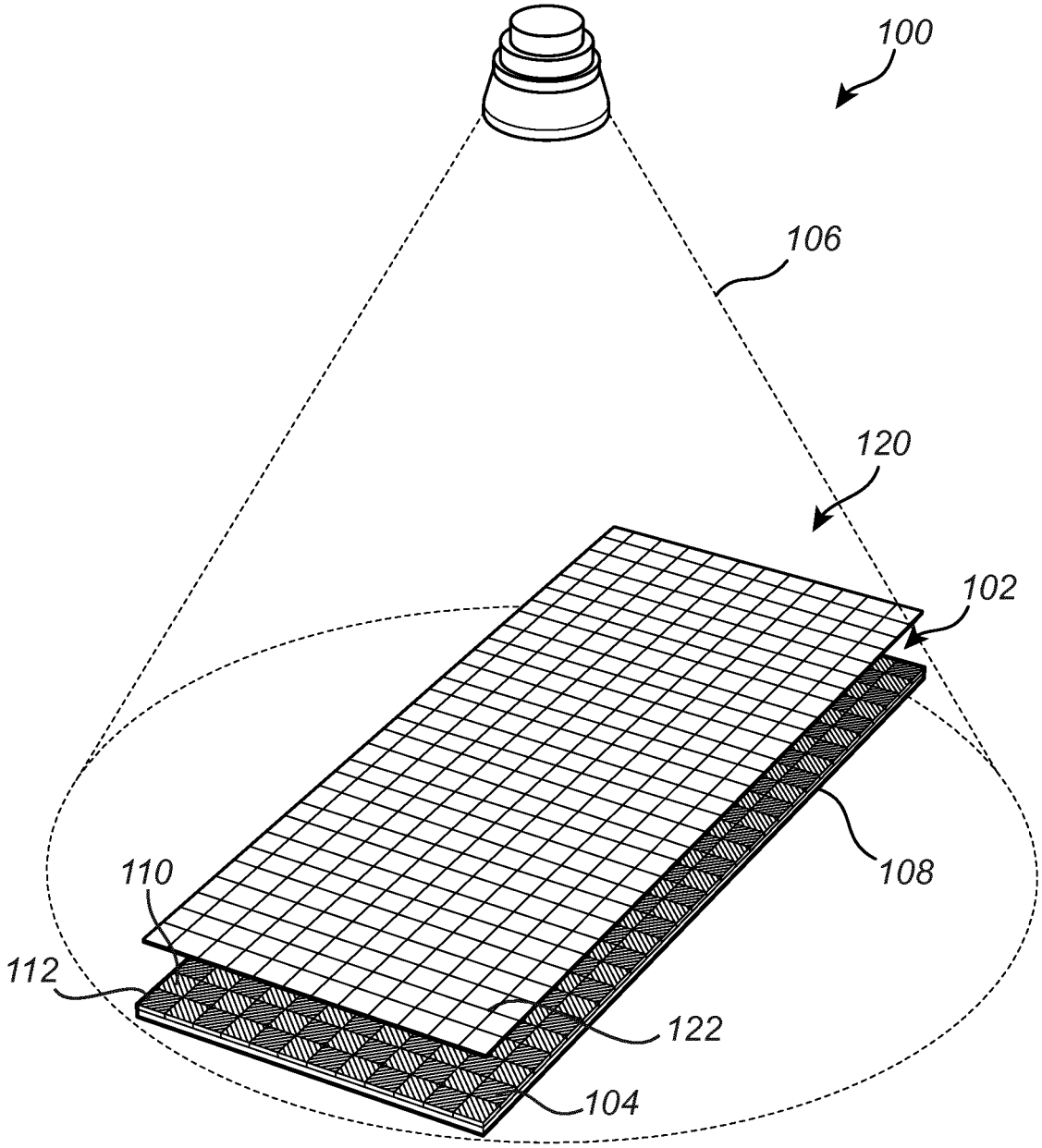


Fig. 1

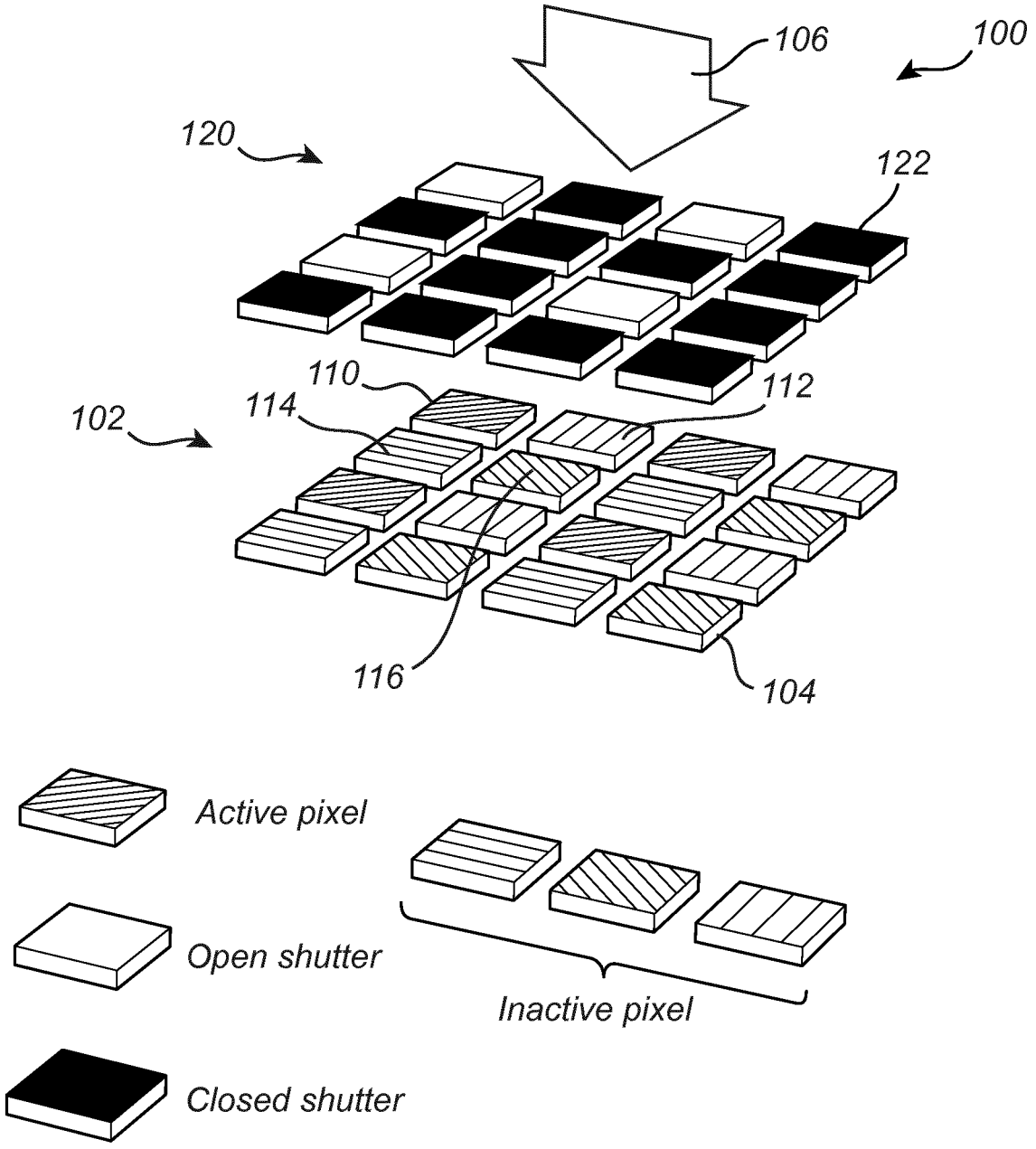

106
100
120
122
110
112
114
102
116
104
Active pixel
Open shutter
Inactive pixel
Closed shutter

Fig. 2a

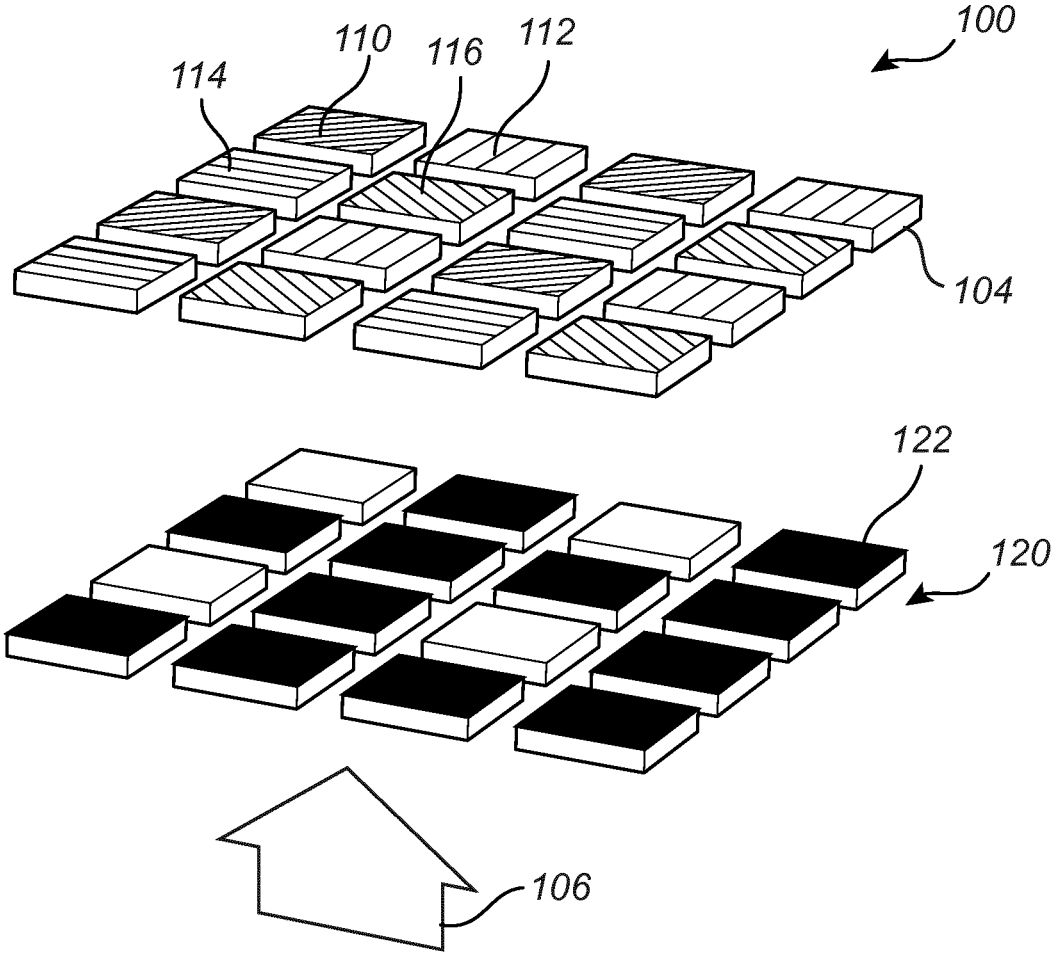


Fig. 2b

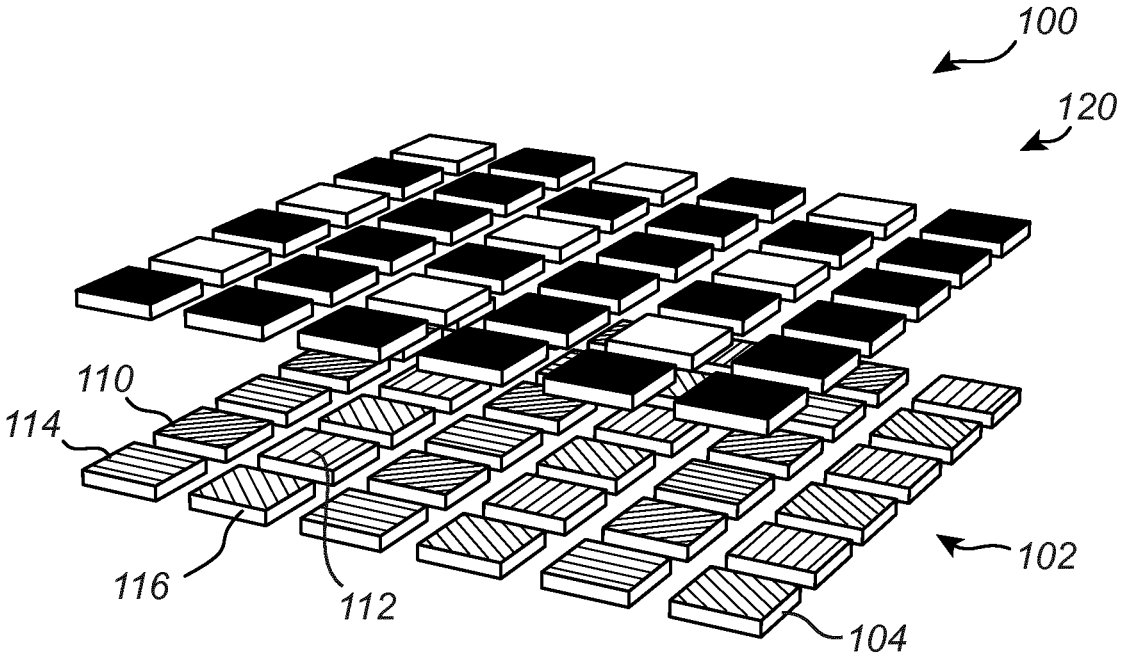


Fig. 3a

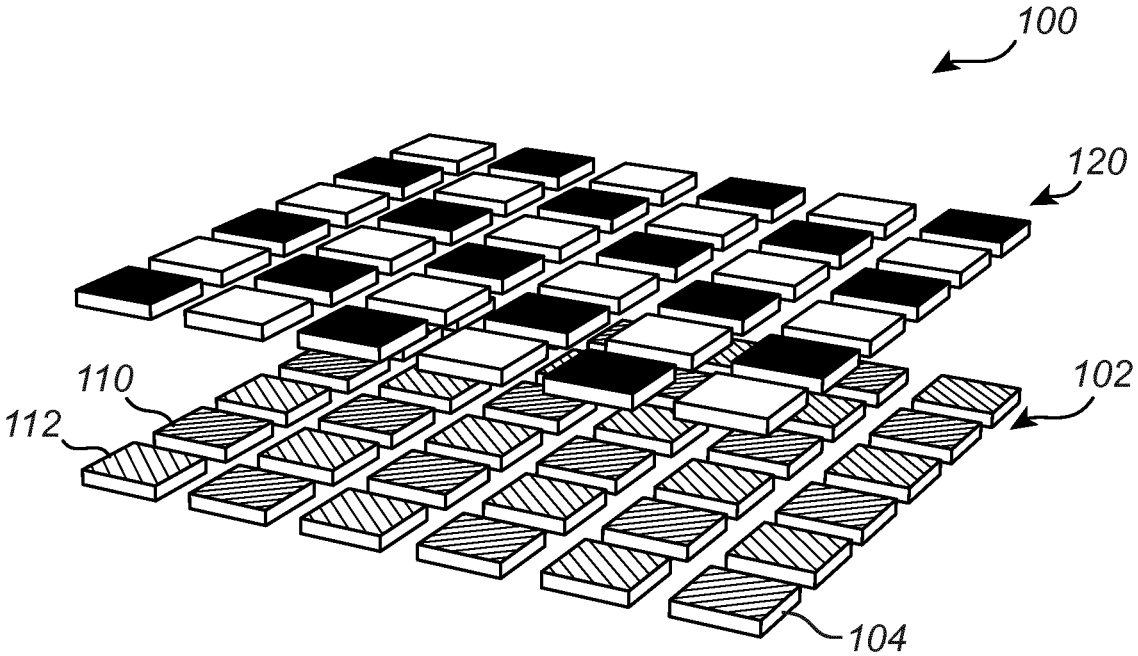


Fig. 3b

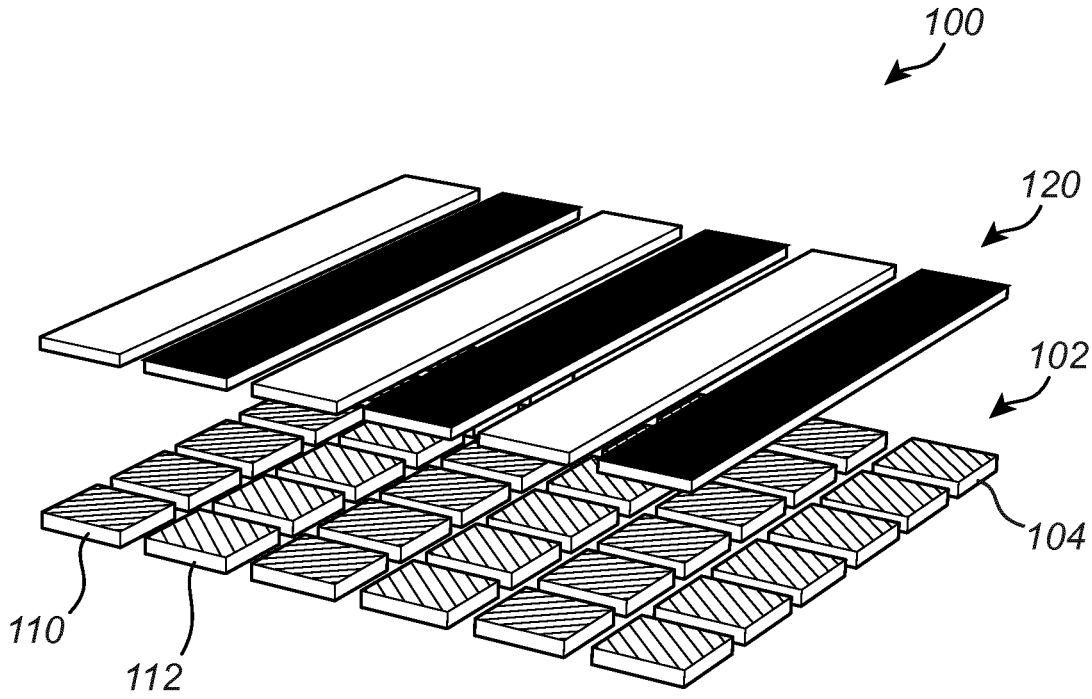


Fig. 4a

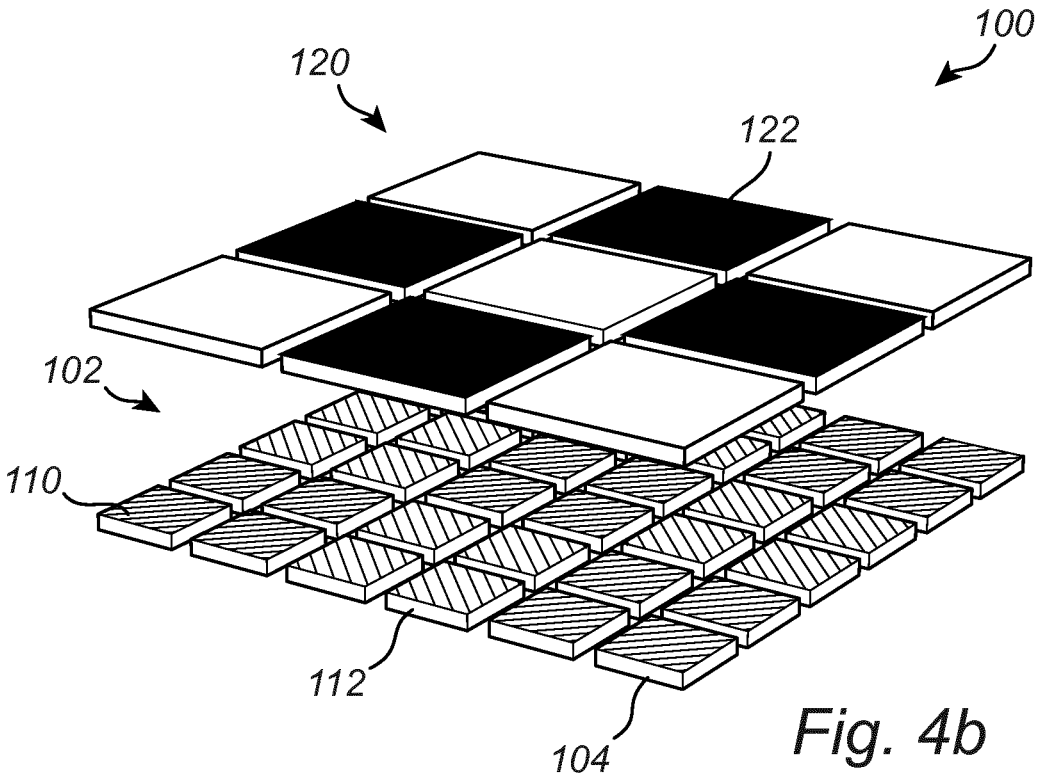


Fig. 4b

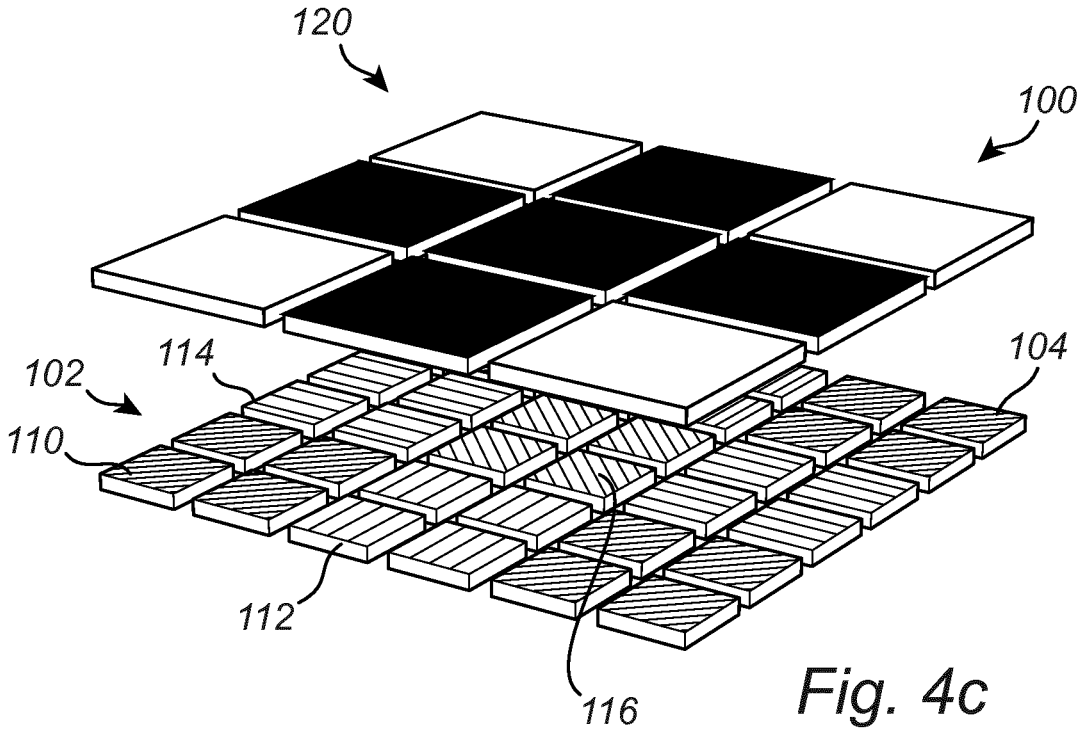


Fig. 4c

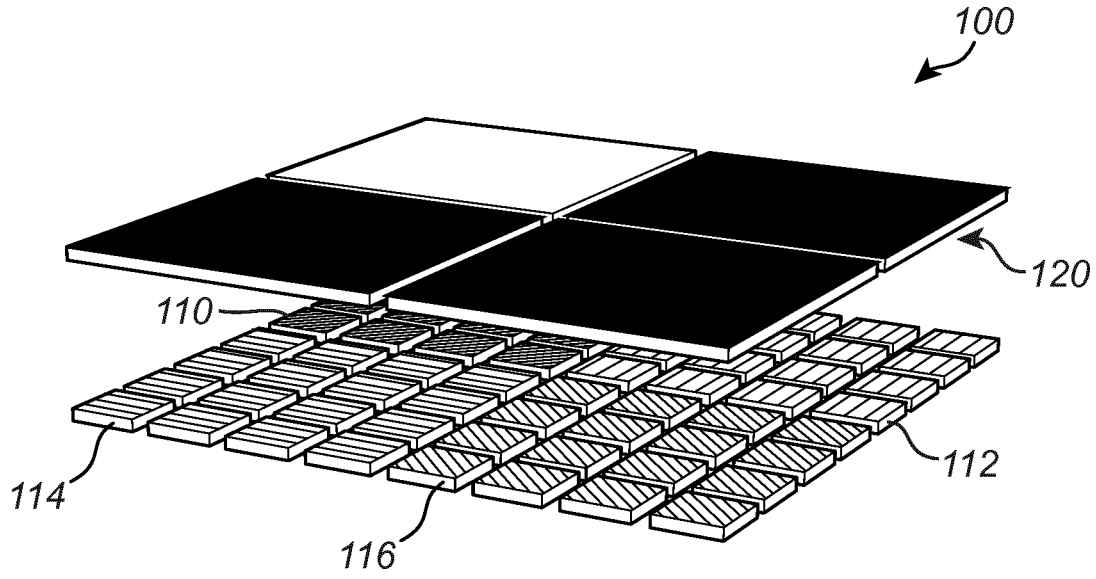


Fig. 4d

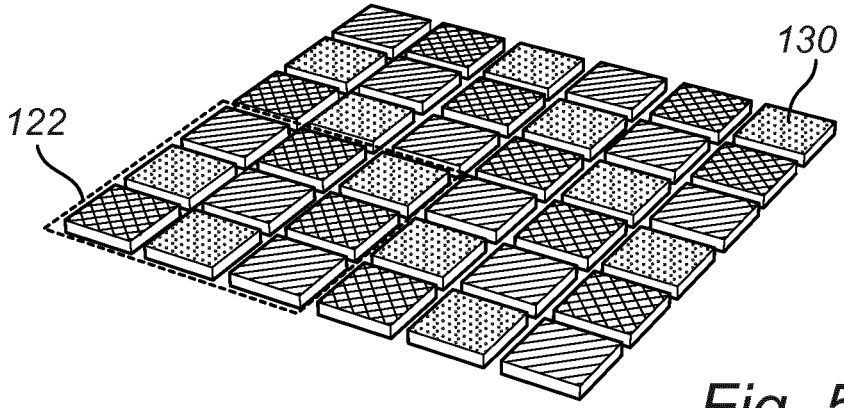


Fig. 5a

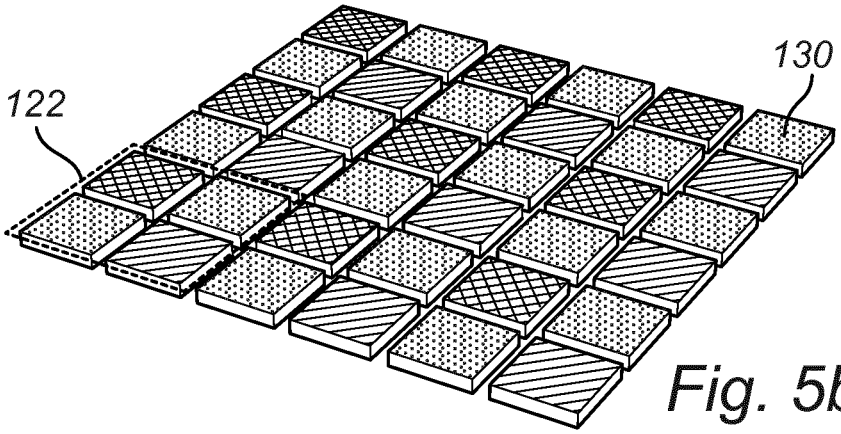


Fig. 5b

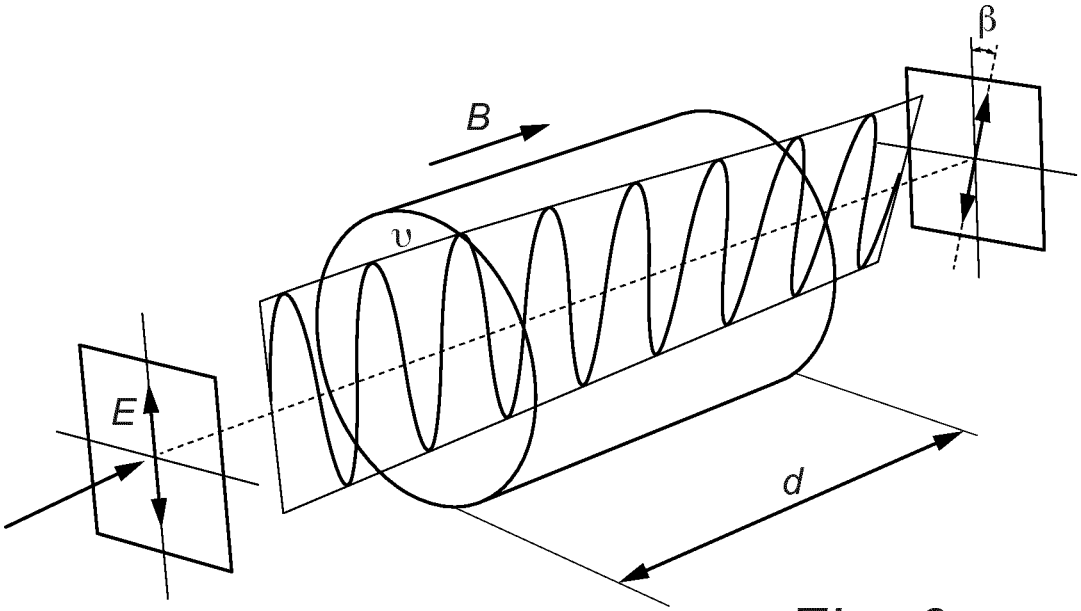


Fig. 6

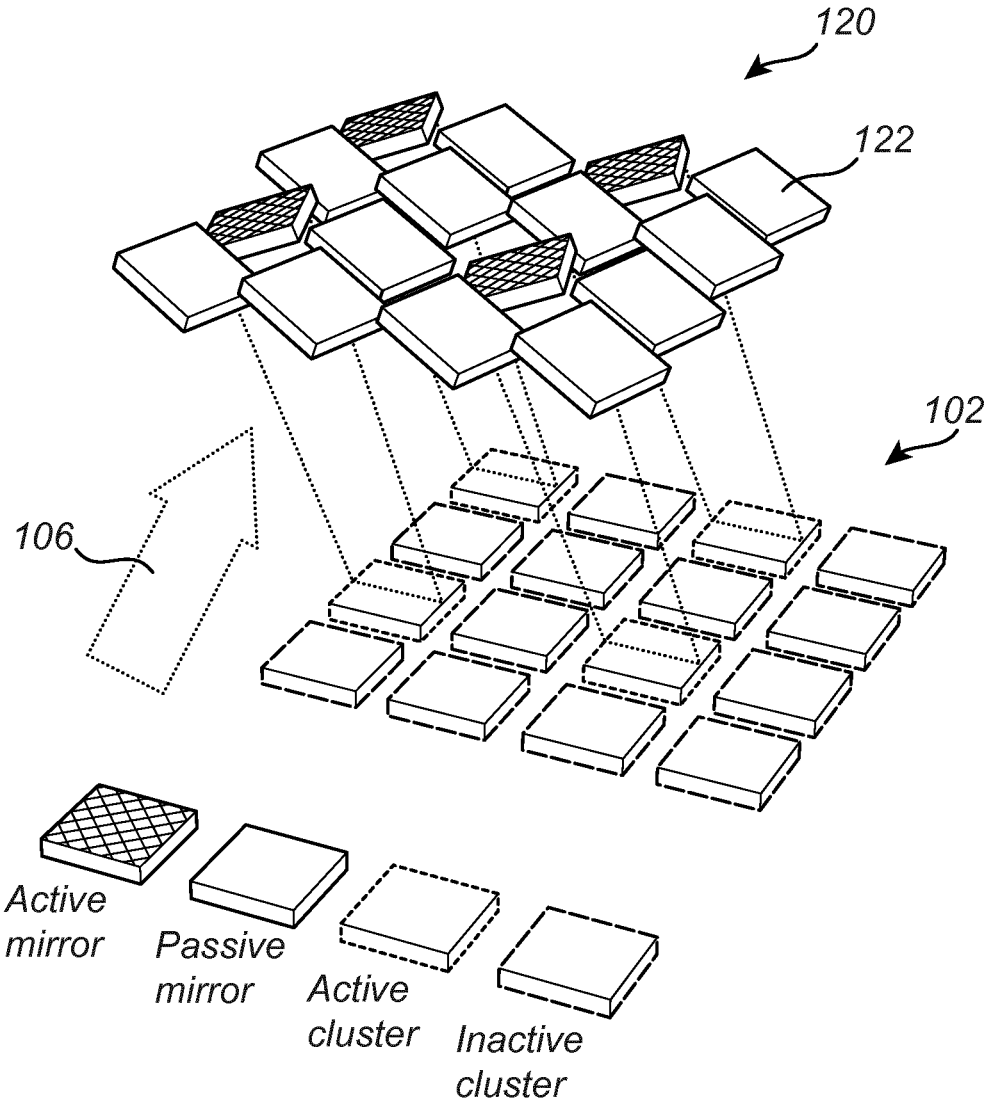

120
122
102
106
Active mirror
Passive mirror
Active cluster
Inactive cluster

Fig. 7

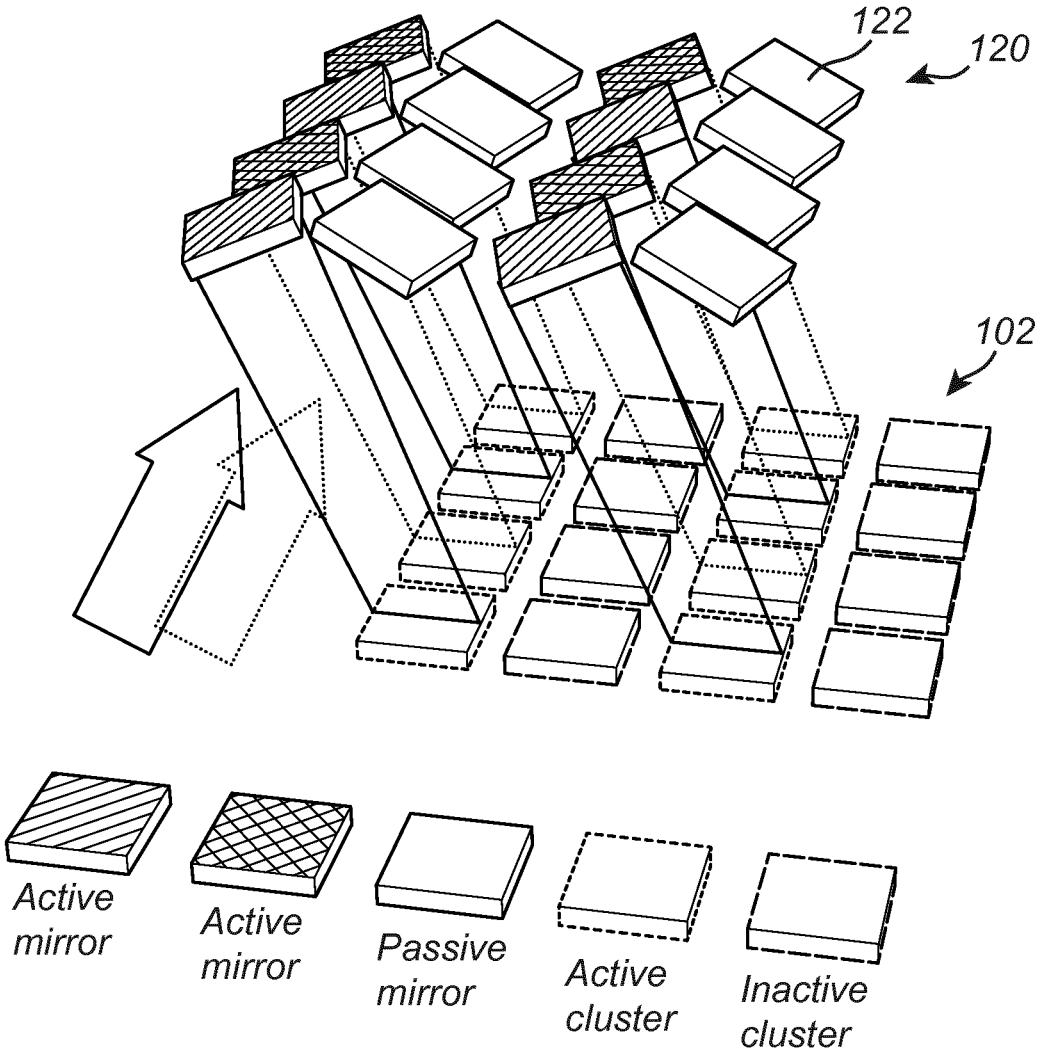

122
120
102
Active mirror
Active mirror
Passive mirror
Active cluster
Inactive cluster

Fig. 8

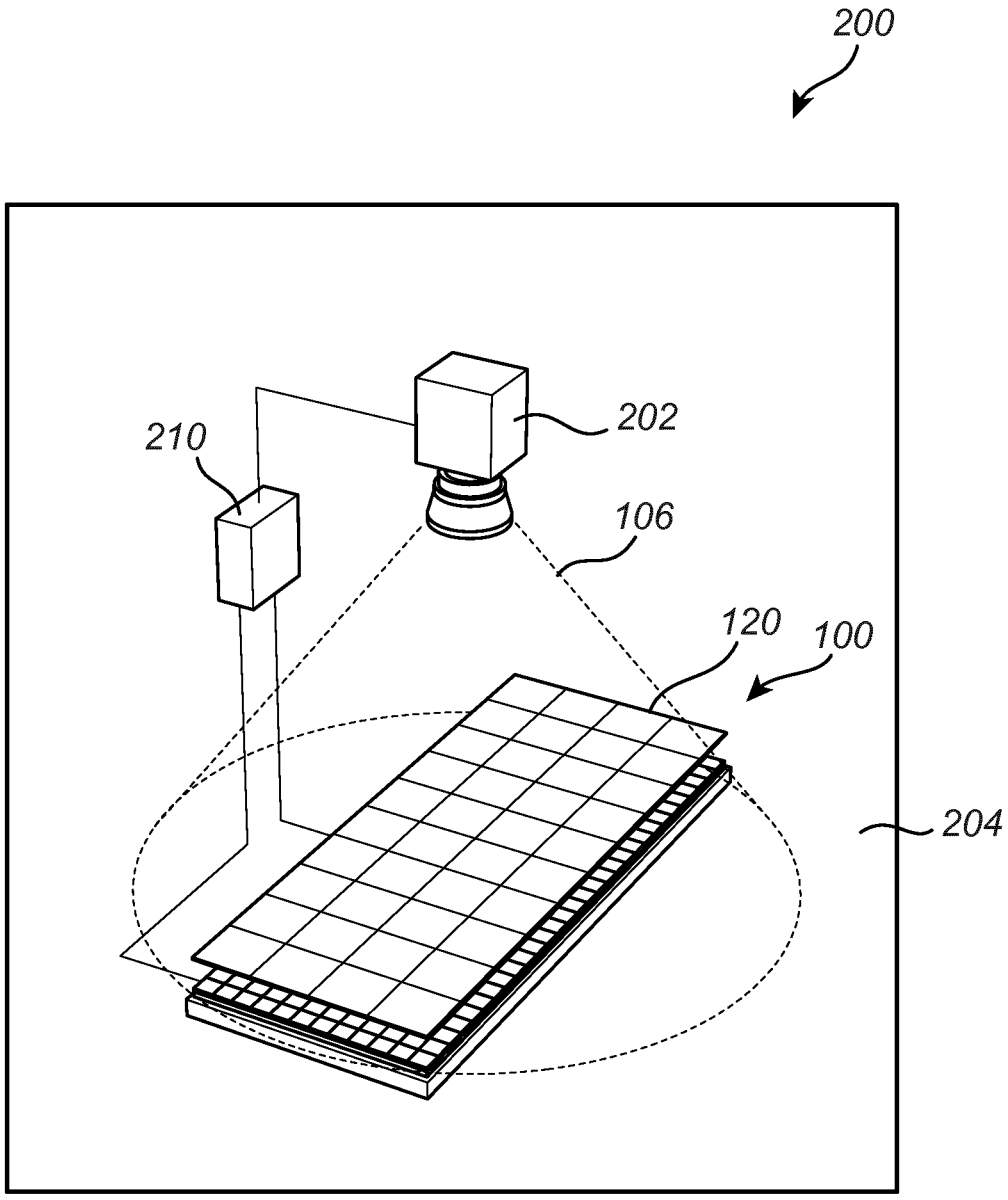


Fig. 9

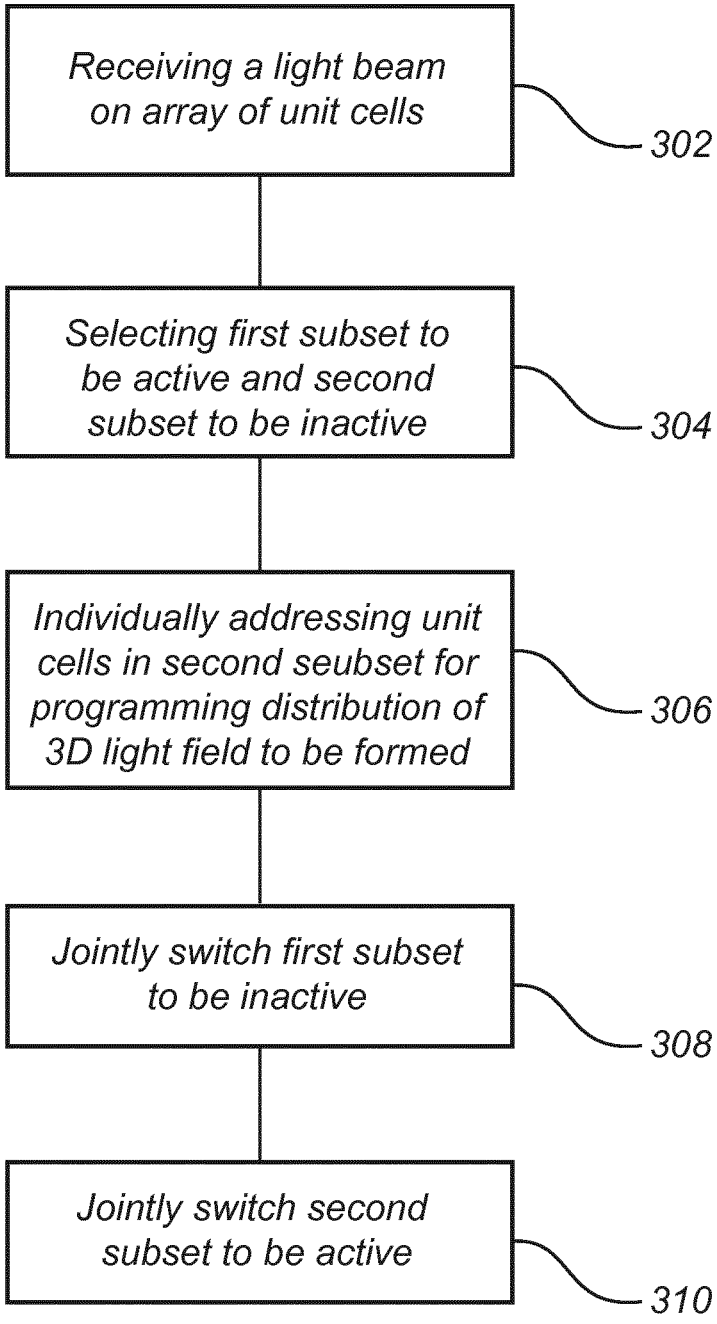

Receiving a light beam on array of unit cells
302
Selecting first subset to be active and second subset to be inactive
304
Individually addressing unit cells in second seubset for programming distribution of 3D light field to be formed
306
Jointly switch first subset to be inactive
308
Jointly switch second subset to be active
310

Fig. 10

OPTICAL DEVICE, A SYSTEM AND A METHOD FOR FORMING A DISTRIBUTION OF A THREE-DIMENSIONAL LIGHT FIELD

TECHNICAL FIELD

[0001] The present inventive concept relates to an optical device for forming a distribution of a three-dimensional light field. In particular, the present inventive concept relates to an optical device which may form a three-dimensional light field to display a holographic image.

BACKGROUND

[0002] A holographic image is formed by a three-dimensional control of a light field. In particular, if it is desired to present a changing holographic image, such as in presenting of holographic video, an optical device for forming the three-dimensional light field may need to be controlled so as to change properties.

[0003] An optical device for forming a distribution of a three-dimensional light field may comprise an array of unit cells. The array of unit cells may interact with an incident light beam in order to together form a desired three-dimensional light field. The unit cells may thus need to be controlled in order to control interaction with light of each of the unit cells such that the desired three-dimensional light field is formed. Therefore, when a new holographic image is to be presented, a large number of unit cells need to be reconfigured to the desired state in order to change the holographic image being presented.

[0004] Thus, holographic video projectors require writing of large amounts of data in the array of unit cells. For a typical holographic video projector, tens of Gb of data needs to be written with a pitch (distance between adjacent unit cells) of 100 nm in a time frame in the order of 10 ms in order for an experience to a viewer watching the holographic video not to be hampered.

[0005] The writing of such amounts of data is a very difficult task.

SUMMARY

[0006] An objective of the present inventive concept is to provide an improved optical device, which may be used for improved control of distribution of a three-dimensional light field. A specific objective of the present inventive concept is to provide an optical device, which at least alleviates a problem of writing very large amounts of data to an array of unit cells for displaying of holographic video.

[0007] These and other objectives of the invention are at least partly met by the invention as defined in the independent claims. Preferred embodiments are set out in the dependent claims.

[0008] According to a first aspect, there is provided an optical device for forming a distribution of a three-dimensional light field, said optical device comprising: an array of unit cells, wherein a unit cell in the array of unit cells is individually addressable for controlling an optical property of the unit cell, wherein addressing of the unit cell is configured to switch the optical property of the unit cell between a first condition of the optical property and a second condition of the optical property; wherein the unit cells in the array of unit cells are configured to be selectively active or inactive and wherein the array of unit cells comprise at least a first subset of unit cells and a second subset of unit cells, wherein the first subset and the second subset are disjoint, and wherein the unit cells in a subset of unit cells are configured to be jointly switched from being inactive to being active, wherein the active unit cells are configured to interact with an incident light beam and cooperate in forming the distribution of the three-dimensional light field; and wherein the optical device is configured to address inactive unit cells for switching the optical property of unit cells when the unit cells are inactive.

[0009] Thanks to the optical device according to the first aspect, an array of unit cells comprises a first and a second subset. Unit cells may thus be selectively inactive or active, wherein only the active unit cells contribute to the forming of a distribution of the three-dimensional light field at a given point in time. This implies that the inactive unit cells may be addressed, while being inactive, for writing information representing a next holographic image to be displayed into the inactive unit cells. The writing of information is performed by controlling a condition of the optical property of the respective unit cells. Thus, there is a relatively lenient requirement on a writing time for providing the information on the next holographic image to the inactive unit cells, as the information may be written while a previous image is being displayed.

[0010] The use of at least a first subset and a second subset of unit cells implies that all unit cells are not simultaneously used in forming of the distribution of the three-dimensional light field. Hence, a trade-off of resolution, brightness and quality of a holographic image may be made in order to enable writing large amounts of information to the array of unit cells for displaying a holographic video.

[0011] The unit cells may need to be individually addressed in order to switch a condition of the optical property of the unit cells for forming a desired distribution of the three-dimensional light field. Each unit cell may have an individually set condition of the optical property such that the desired distribution is formed. This implies that the unit cells may need to be addressed individually in order to control the condition of the optical property of each unit cell, which is a time-consuming operation or requires a very large number of parallel control lines for addressing the unit cells. However, by performing the individual addressing of unit cells to inactive unit cells while a holographic image is displayed based on active unit cells, there is a substantial increase in the available time for addressing of unit cells (as a typical frame rate of 25 frames per second correspond to a single image being displayed for a period of approximately 40 ms).

[0012] The switching of a subset of unit cells from being inactive to being active (or vice versa) may be performed in a very fast manner. Since the conditions of the optical properties of the unit cells of the subset have been set in individual addressing of the unit cells, a common operation may be performed to all the unit cells in the subset for ensuring that the unit cells in the subset are switched from being inactive to being active. Thus, the unit cells in the subset may be jointly switched from being inactive to being active using a single control signal that applies to all the unit cells in the subset.

[0013] The joint switching of the unit cells from being inactive to being active may be performed using a single control signal such that all unit cells in the subset may be switched simultaneously. However, it should be realized that the subset may be associated with a plurality of control lines,

wherein each control line may control a plurality of unit cells in the subset. Thus, the joint switching may be performed using a sequence of control signals on the plurality (but small number) of control lines so as to switch the unit cells from being inactive to being active. The joint switching may still be performed in such a short time as to not affect experience of a viewer looking at a holographic video.

[0014] The joint switching of the unit cells should thus be construed as the unit cells being simultaneously switched or, if the switching is not exactly simultaneously performed, it should be performed fast enough as to not hamper viewer experience. This may be realized by common operation may be controlled in a pre-defined manner. For instance, the common operation may be triggered by a packet of control signals forming a sequence of control signals supplied on a plurality of control lines.

[0015] As will be exemplified in various embodiments below, the switching of the unit cells from being inactive to being active may be performed e.g. using a light shutter structure associated with the unit cells.

[0016] It should be realized that the array of unit cells may comprise more than two mutually disjoint subsets of unit cells. This may provide even more time for individually addressing the unit cells in a subset for writing information to the unit cells. The unit cells of a subset are only active for ⅓ of the time using three subsets, ¼ of the time using four subsets, and so on. However, in some implementations, a resolution of the holographic image may be even more affected if further subsets of unit cells are used.

[0017] It should be realized that the forming of the distribution of a three-dimensional light field may be used in several different applications, such as in displaying of holographic video as discussed above, e.g. in any type of application for controlled illumination.

[0018] It should also be realized that the distribution of the three-dimensional light field based on an active subset may contribute only to part of a holographic image that is perceived by a viewer. Based on persistence of vision, holographic images formed in a fast sequence may be perceived as together displaying a complete holographic image. Thus, the distribution of a three-dimensional light field formed based on a first active subset may together with the distribution of a three-dimensional light field formed based on a second active subset, shortly after the distribution of the first active subset was formed, be perceived by a viewer as a complete holographic image.

[0019] According to an embodiment, the unit cells of the first subset are arranged interleaved with the unit cells of the second subset in the array of unit cells.

[0020] This implies that the unit cells of the first subset may be spread out over the entire array of unit cells. Likewise, the unit cells of the first subset may be spread out over the entire array of unit cells.

[0021] In one embodiment, every other unit cell is part of the first subset and every other unit cell is part of the second subset. This implies that each unit cell of the first subset is arranged in-between two unit cells of the second subset and that each unit cell of the second subset is arranged between two unit cells of the first subset. In such embodiment, the unit cells in a subset are evenly spread out over the entire array of unit cells, which may facilitate forming of a holographic image of high quality throughout a series of sequentially projected holographic images.

[0022] In another embodiment, the unit cells of each subset may be spread out in clusters of n×m unit cells. Each cluster of unit cells of the first subset may be arranged between two clusters of unit cells of the second subset, and vice versa.

[0023] It should be realized that other configurations of interleaved subsets are possible. In particular, the array of unit cells may comprise more than two subsets, wherein the unit cells of all subsets may be interleaved. The unit cells in a subset may e.g. form a regular pattern in the array of unit cells, such that single unit cells or cluster of unit cells belonging to the subset may be evenly distributed in the array of unit cells.

[0024] According to an embodiment, the first subset of unit cells forms a first sub-array of unit cells and the second subset of unit cells forms a second sub-array of unit cells and wherein the first sub-array and the second sub-array are arranged adjacent to each other on a common substrate.

[0025] This implies that each subset of unit cells may be associated with a separate area in the array of unit cells. Hence, a distance between two adjacent unit cells that are part of the same subset is equal to the distance between two adjacent unit cells in the array of unit cells. Therefore, using such arrangement of the subset, a resolution of a holographic image need not be affected by the array of unit cell being divided into two or more subsets.

[0026] However, the plural subsets still imply that all unit cells are not simultaneously used when displaying a holographic image at a given point in time. Therefore, the entire array of unit cells may still need to be larger than an array of unit cells that would not be divided into plural subsets.

[0027] According to an embodiment, each subset of unit cells comprise first unit cells configured to interact with a first wavelength of light and second unit cells configured to interact with a second wavelength of light different from the first wavelength of light.

[0028] This implies that the optical device may be configured to form a distribution of a three-dimensional light field for multiple wavelengths, such that a multi-color holographic image may be formed. Each of the subsets may thus comprise first unit cells dedicated for interaction with a first wavelength and second unit cells dedicated for interaction with a second wavelength, so as to enable displaying of a multi-color holographic image at any given time when only the unit cells of a single subset may be active.

[0029] An active subset may receive a sequence of incident light beams of different wavelengths. Thanks to persistence of vision, a viewer looking at a holographic image may perceive a fast sequence of holographic images formed by illuminating an active subset by a sequence of incident light beams of different colors as a single multi-color holographic image.

[0030] It should be realized that the optical device may be configured to form multi-color images using more than two wavelengths, such that each subset of unit cells may then also comprise third unit cells configured to interact with a third wavelength, and so on.

[0031] In one embodiment, a unit cell may be associated with a color filter for controlling a wavelength of light with which the unit cell will interact.

[0032] According to an embodiment, the optical device further comprises a light shutter structure arranged in relation to the array of unit cells, wherein the light shutter structure is controllable for selecting whether incident light

on the light shutter structure reaches a unit cell with which the light shutter structure is associated for selecting whether the unit cell is being inactive or being active.

[0033] The light shutter structure may be integrated with a substrate on which the array of unit cells is formed. However, the light shutter structure may alternatively be arranged separately from the substrate and may e.g. be associated with a light source or arranged between the light source and the array of unit cells.

[0034] The light shutter structure may be arranged such that unit cells of a subset are associated with the light shutter structure in such a manner that when the light shutter structure is controlled, the unit cells in the subset will be jointly switched from being inactive to being active (or vice versa).

[0035] According to an embodiment, the light shutter structure comprises a first light shutter which is shared by the first subset of unit cells and a second light shutter which is shared by the second subset of unit cells.

[0036] Thus, the first light shutter may be associated with all unit cells of the first subset and the second light shutter may be associated with all unit cells of the second subset. This implies that controlling of the first light shutter may jointly switch the unit cells of the first subset from being inactive to being active or vice versa. Similarly, controlling of the second light shutter may jointly switch the unit cells of the second subset from being inactive to being active or vice versa.

[0037] Hence, the first light shutter may be formed as a single structure, which may be controlled by a single control signal, and the second light shutter may be formed as another single structure, which may also be controlled by a single control signal (different from the control signal controlling the first light shutter). For instance, the first light shutter and/or the second light shutter may comprise a plurality of lines arranged above the unit cells of the subset associated with the light shutter. The plurality of lines may be interconnected, e.g. at an end, such that a single control signal may switch the unit cells of the subset from being inactive to being active or vice versa.

[0038] According to an embodiment, the light shutter structure comprises an array of light shutter units, wherein each light shutter unit is associated with a single unit cell, and wherein the light shutter units associated with the first subset are configured to be jointly controlled for switching the unit cells in the first subset from being inactive to being active.

[0039] Thus, the light shutter structure may comprise separate light shutter units forming a one-to-one relationship between light shutter units and unit cells in the array. Since a common operation is to be performed on the light shutter units associated with a subset when the unit cells of the subset are to be switched from being active to being inactive, the light shutter units need not be individually addressed for providing a control signal for switching a state of the light shutter units. Rather, the light shutter units associated with the first subset may be configured to be jointly controlled, e.g. so that control signals are simultaneously or jointly provided to the light shutter units associated with the first subset.

[0040] According to an embodiment, the optical device comprises a control unit providing control signals to the light shutter structure, wherein a control signal is configured to control whether incident light on the light shutter structure reaches a unit cell with which the light shutter structure is associated based on changing a state of a phase-change material, changing a state of a liquid crystal for controlling light passing through polarization filters, inducing an electro-optical effect, inducing a magneto-optical effect, changing a polarization of light being transmitted by a polarization filter, activating a movement of an actuator in a microelectromechanical or nano-electromechanical system, or activating a macroscopic mechanical shutter.

[0041] Thus, a function of controlling whether incident light is to be received by a unit cell in a subset may be achieved in various ways. The way of controlling whether incident light on the light shutter structure is allowed to pass to a unit cell may be chosen e.g. in relation to effectiveness of preventing light from reaching the unit cell, size of a controlling structure, a pitch of light shutter units and/or complexity of the controlling structure.

[0042] According to an embodiment, the light shutter structure comprises control lines for sending control signals for selecting whether incident light on the light shutter structure reaches a unit cell with which the light shutter structure is associated. The control signals may be configured to trigger a local function in the unit cell for switching a condition of an optical property of the unit cell.

[0043] In another embodiment, the optical device comprises a control unit providing control signals to the light shutter structure, wherein the light shutter structure is arranged to receive light being transmitted by the array of unit cells, and wherein a control signal is configured to control whether incident light on the light shutter structure is allowed to contribute to the forming of the distribution of the three-dimensional light field. The control of the light shutter structure may be based on changing a state of a phase-change material, changing a state of a liquid crystal for controlling light passing through polarization filters, inducing an electro-optical effect, inducing a magneto-optical effect, changing a polarization of light being transmitted by a polarization filter, activating a movement of an actuator in a microelectromechanical system, or activating a macroscopic mechanical shutter.

[0044] According to an embodiment, the optical device comprises a set of passive polarization filters arranged in relation to the array of unit cells, wherein the first subset of unit cells is associated with a first polarization filter configured to transmit light of a first polarization, and wherein the second subset of unit cells is associated with a second polarization filter configured to transmit light of a second polarization different from the first polarization.

[0045] The set of passive polarization filters may be integrated with a substrate on which the array of unit cells is formed. However, the set of passive polarization filters may alternatively be arranged separately from the substrate and may e.g. be associated with a light source or arranged between the light source and the array of unit cells.

[0046] Each subset may thus be associated with a specific polarization of light. Hence, by switching a polarization of light of the incident light beam, unit cells of a subset may be switched from being inactive to being active.

[0047] The first polarization filter and the second polarization filter may be configured to transmit orthogonal linear polarization states of incident light or left-handed circular polarization state and right-handed circular polarization state, respectively.

[0048] According to an embodiment, the unit cells comprise a phase-change material, which may be switched between a first state and a second state, wherein switching of the phase-change material between the first state and the second state is configured to switch the optical property of the unit cell between a first condition of the optical property and a second condition of the optical property.

[0049] A phase-change material may be advantageously used for controlling a condition of the optical property of a unit cell. For instance, reflectivity or transmission of a unit cell may be highly dependent on a state of the phase-change material. Hence, by switching state of the phase-change material of a unit cell, contribution of the unit cell to the forming of the distribution of the three-dimensional light field may be controlled. Thus, by setting states of each of the unit cells in a subset, a desired distribution of the three-dimensional light field may be defined.

[0050] The phase-change material may be combined with other materials, e.g. in a stack of layers of materials, wherein a state of the phase-change material may control a condition of an optical property of the stack of layers of materials. It should thus be realized that the unit cell may be formed in various configurations including a phase-change material.

[0051] A switching of a state of a phase-change material may be induced in many different manners, e.g. by thermal activation or exerting the phase-change material to an electric or magnetic field. It should be realized that the controlling of the state of the phase-change material may be provided by individually addressing the unit cell, e.g. by sending a control signal to electrodes associated with the unit cell for inducing the switching of the state of phase-change material locally in the unit cell.

[0052] According to an embodiment, the active unit cells are configured to cooperate in reflecting an incident light beam for forming the distribution of the three-dimensional light field.

[0053] According to another embodiment, the active unit cells are configured to cooperate in transmitting an incident light beam for forming the distribution of the three-dimensional light field.

[0054] Thus, it should be realized that the optical device may be configured either for reflective or transmissive forming of the distribution of the three-dimensional light field. The choice whether the optical device should be configured to be reflective or transmissive may be made depending on a desired application. Also, some techniques for implementing the light shutter structure may be more suited e.g. for using a transmissive optical device, such as if using a light shutter structure which is configured to reflect an incident light beam for inactive unit cells.

[0055] According to a second aspect, there is provided a system for forming a distribution of a three-dimensional light field, said system comprising: the optical device according to the first aspect; and a light source configured to emit a light beam to be incident on the array of unit cells.

[0056] Effects and features of this second aspect are largely analogous to those described above in connection with the first aspect. Embodiments mentioned in relation to the first aspect are largely compatible with the second aspect.

[0057] Thus, the system may comprise both an optical device for controlling the distribution of the three-dimensional light field and a light source for providing a light beam for forming the three-dimensional light field when interacting with the optical device.

[0058] The system may comprise a housing in which the optical device and the light source are mounted, such that a well-controlled and pre-defined relationship between the light source and the optical device may be provided.

[0059] According to an embodiment, the system further comprises a controller for controlling a polarization of light emitted by the light source.

[0060] The polarization of light may be used for switching which unit cells are active, e.g. when using a set of passive polarization filters. The controller may thus control that the polarization of light emitted by the light source is switched at an appropriate point in time for forming of a desired distribution of the three-dimensional light field.

[0061] The controller may be configured to also control individual addressing of the unit cells for writing information to inactive unit cells for a next holographic image to be displayed. However, the system may alternatively comprise a separate controller for controlling switching of the condition of the optical property of the unit cells. In such case, the plural controllers may be synchronized for ensuring that changing of polarization of light emitted by the light source is performed at an appropriate point in time.

[0062] According to a third aspect, there is provided a method for forming a distribution of a three-dimensional light field, said method comprising:

[0063] receiving a light beam incident on an array of unit cells; selecting a first subset of unit cells to be active and a second subset of unit cells to be inactive, wherein the first subset of unit cells is disjoint from the second subset of unit cells; individually addressing the unit cells in the second subset of unit cells, while the unit cells in the second subset are inactive, in order to control the optical property of the unit cell to one of at least a first condition of the optical property and a second condition of the optical property, wherein the second subset of unit cells is programmed by the individual addressing of the unit cells for forming a distribution of the three-dimensional light field; jointly switching the first subset of unit cells to be inactive; and jointly switching the second subset of unit cells to be active for changing the distribution of the three-dimensional light field to the distribution programmed in the second subset of unit cells.

[0064] Effects and features of this third aspect are largely analogous to those described above in connection with the first and second aspects. Embodiments mentioned in relation to the first and second aspect are largely compatible with the third aspect.

[0065] The method enables writing of information to inactive unit cells, such that a relatively lenient requirement on a writing time is provided even if a holographic video is to be presented based on the forming of distribution of the three-dimensional light field. Further, the unit cells of a subset may be jointly switched from being inactive to being active or vice versa for very fast switching between a current distribution of the three-dimensional light field and a next distribution of the three-dimensional light field, e.g. in switching from a current frame to a next frame in a holographic video.

BRIEF DESCRIPTION OF THE DRAWINGS

[0066] The above, as well as additional objects, features and advantages of the present inventive concept, will be

better understood through the following illustrative and non-limiting detailed description, with reference to the appended drawings. In the drawings like reference numerals will be used for like elements unless stated otherwise.

[0067] FIG. **1** is a schematic view of an optical device according to an embodiment.

[0068] FIGS. **2***a-b* are schematic views illustrating optical devices in a reflective and a transmissive geometry.

[0069] FIGS. **3***a-b* and **4***a-d* are schematic views illustrating embodiments of defining subsets of unit cells in an array of unit cell of an optical device.

[0070] FIGS. **5***a-b* are schematic views illustrating color filters used with an optical device.

[0071] FIG. **6** is a schematic view illustrating a principle of a Faraday rotator.

[0072] FIGS. **7-8** are schematic views illustrating light shutter structures of an optical device, where the light shutter structures are implemented using a MEMS based micro-mirror system.

[0073] FIG. **9** is a schematic view of a system according to an embodiment.

[0074] FIG. **10** is a flowchart illustrating a method according to an embodiment.

DETAILED DESCRIPTION

[0075] Referring now to FIG. **1**, an optical device **100** will be generally described. The optical device **100** may comprise an array **102** of unit cells **104**. Unit cells in the array **102** of unit cells **104** may be individually addressable for controlling an optical property of the unit cell **104** and hence controlling an optical response of the array **102** of unit cells **104**.

[0076] Each unit cell **104** may be individually addressable. However, it should be realized that not necessarily each and every one of the unit cells **104** is individually addressable.

[0077] By controlling the optical property of the unit cells **104**, an effect on a light beam **106** incident on the array **102** may be controlled. Thus, the unit cells **104** may in combination form a controllable effect on the incident light beam **106**. Thus, the array **102** may be used for forming and controlling a distribution of a three-dimensional light field based on the incident light beam **106**

[0078] The three-dimensional light field may for instance be used for displaying a holographic image. Thanks to the unit cells **104** being controllable, a change in the holographic image formed may be provided. This implies that the optical device **100** may be used for displaying a video of holographic images.

[0079] However, it should be realized that control of a three-dimensional light field may be useful in other applications as well. The optical device **100** for forming a three-dimensional light field may project a controlled distribution in three dimensions of an incident light beam, which may be used in any type of application for controlled illumination and need not necessarily be combined with forming of a displayed image based on the three-dimensional light field.

[0080] The optical device **100** may be set up for reflecting the incident light beam **106** or transmission of the incident light beam **106**. The light beam **106** may be formed by a coherent light source, such as the light beam **106** being a laser beam, which provides a well-defined relation of the incident light field on the array **102** of unit cells **104** and, hence, is suitable for using as a basis for forming the desired distribution of the three-dimensional light field using the array **102** of unit cells **104**.

[0081] Each unit cell **104** may comprise a phase-change material (PCM), which may be switched between a first state and a second state, wherein switching of the PCM between the first state and the second state is configured to switch the optical property of the unit cell **104** between a first condition of the optical property and a second condition of the optical property.

[0082] The PCM may be configured to switch between a crystalline state and an amorphous state. However, it should be realized that the first and second states may be other configurations of states of the PCM. For instance, the PCM may be configured to switch between two different crystalline states.

[0083] The unit cell **104** may comprise a layer of PCM, which may be combined with other materials, e.g. in a stack of layers of materials, such that the combination of materials may define an optical property of the unit cell. The switching of a state of the PCM may then affect the optical property of, for instance, the stack of layers in the unit cell **104**, such that a condition of the optical property of the unit cell **104** may be controlled by a state of the PCM.

[0084] For instance, the switching of state of the PCM may affect refractive index and/or permittivity of the PCM, such that e.g. a PCM layer or a stack comprising a PCM layer may be switched from a highly reflective to a low reflective state for a given wavelength of incident light.

[0085] The unit cell **104** may thus comprise a PCM layer for controlling a condition of the optical property of the unit cell **104**. For instance, reflectivity or transmission of the unit cell for a given wavelength may be configured to be highly dependent on the state of the PCM.

[0086] According to an embodiment, the PCM is a compound of germanium, antimony and tellurium. For instance, the PCM may be formed by $Ge_2Sb_2Te_5$ (GST). This is a material which may change between an amorphous state and a crystalline state and which may suitably be used for providing desired optical properties of the array **102** of unit cells **104**.

[0087] However, it should be realized that the PCM may be any material which provides a change in optical property based on the switching between two states. The PCM may for instance be any material which may undergo a phase change in relation to being exposed to a temperature (a thermochromic material) or in relation to being exposed to light (a photochromic material) or a combination of such materials. For example, a number of different forms of vanadium oxides, such as VO_2 and V_2O_3, may be used. The PCM may include thermochromic materials formed from metal-oxide materials, such as vanadium oxide as mentioned above, polymers, such as azobenzene-containing polydiacetyelenes, or nanostructured polymers, such as diblock (poly[styrene-b-isoprene]) copolymers. The PCM may alternatively be an electro-optic material that changes a condition of an optical property based on an applied electric field, such as a birefringent material, or a magneto-optic material that changes a condition of an optical property based on an applied magnetic field, such as garnets and ferro-magnetic metals.

[0088] In the specific case of using GST as the PCM, switching the material modifies the structure from a plasmonic (crystalline state) to a dielectric (amorphous state)

antenna, which will exhibit very similar resonances but at different wavelengths, allowing to change a structure in the unit cell **104** from a highly reflective to a low reflective state for a given wavelength.

[0089] Upon switching of the state of GST, the optical properties are significantly altered, resulting in large changes in both real and imaginary parts of refractive index and permittivity. It should be noted that in its crystalline state, GST has a negative real part of the permittivity, which implies that it shows metallic behavior and therefore supports plasmonic resonances. In its amorphous state, GST has a positive real part of the permittivity, accompanied with a large imaginary part, meaning that it acts as a highly lossy dielectric.

[0090] The PCM in a unit cell **104** could be switched thermally (as for GST) but is not limited to that. It should be realized that in different embodiments, electro-optic materials, and magneto-optic materials may be used as alternative implementations.

[0091] It should be realized that the controlling of the state of the PCM may be provided by individually addressing the unit cell **104**, e.g. by sending a control signal to electrodes associated with the unit cell **104** for inducing the switching of the state of phase-change material locally in the unit cell, e.g. by local heating of the PCM, or by exerting the PCM to a local electric or magnetic field.

[0092] The optical device **100** may suitably be used with visible wavelengths, as this implies that the three-dimensional light field may be seen by people. In many applications, such as for creation of holographic images, use of visible wavelengths is desired. However, the optical device **100** may alternatively be used with other wavelengths, such as near-infrared, infrared, or ultraviolet wavelengths. The unit cells **104** may therefore be configured so that the switching of conditions of an optical property of the unit cell **104** provide a strong effect of the unit cell **104** on a desired operational wavelength.

[0093] The array **102** of unit cells **104** may comprise a plurality of subsets **110**, **112** of unit cells **104**, the subsets **110**, **112** being indicated in FIG. **1** by different hatchings of the unit cells **104**. The subsets **110**, **112** may be disjoint, such that each unit cell **104** in the array **102** is part of a single subset.

[0094] The unit cells **104** in a subset **110**, **112** may be jointly controlled between being active or inactive. When a unit cell **104** is active, the unit cell **104** is part of a set of unit cells **104** which together define a distribution of the three-dimensional light field. When a unit cell **104** is inactive, the unit cell **104** is not part of the set of unit cells **104** for defining the distribution of the three-dimensional light field currently being formed by the optical device **100**.

[0095] Thus, the subsets **110**, **112** may be switched between being active or inactive. For an active subset **110**, **112**, all the unit cells **104** of the subset **110**, **112** are active and contribute to defining a distribution of the three-dimensional light field formed by the optical device **100**. For an inactive subset **110**, **112**, all the unit cells **104** of the subset **110**, **112** are inactive and do not contribute to defining a distribution of the three-dimensional light field formed by the optical device **100**.

[0096] The optical device **100** may have at least one active subset **110**, **112**, when forming a distribution of a three-dimensional light field. Thus, one or more subsets **110**, **112** may be active at a time. For simplicity in determining in which condition of the optical property each unit cell **104** should be set, only a single subset **110**, **112** may be active at a time.

[0097] When a unit cell **104** is inactive, the unit cell **104** does not contribute to the forming of the distribution of the three-dimensional light field. Thus, the unit cell **104** may, while being inactive, be switched for controlling whether the unit cell **104** may be set to the first condition of the optical property or the second condition of the optical property. This implies that the inactive subset **110**, **112** may be prepared, while being inactive, with each unit cell **104** set to a desired condition of the optical property, such that when the subset **110**, **112** is switched from being inactive to being active, the active unit cells **104** in the subset **110**, **112** may immediately ensure that a desired distribution of the three-dimensional light field is formed by the optical device **100**.

[0098] In this manner, the use of inactive subsets **110**, **112**, enables writing of information of a next frame (distribution of a three-dimensional light field) to be written to unit cells **104** in an inactive subset **110**, **112**. Thus, a time for performing the writing operation may be relatively long without e.g. affecting the experience of a viewer watching a holographic video.

[0099] Then, when the optical device **100** is to be updated from forming a current distribution of the three-dimensional light field to forming a next distribution of the three-dimensional light field, a very fast operation may be performed by switching an active subset **110**, **112** to being inactive and switching an inactive subset **110**, **112** to being active.

[0100] A periodicity of active unit cells **104** may be below the operational wavelength in order to ensure that an accurate control of the formed distribution of the three-dimensional light field is obtained. The periodicity may preferably even be below half of the operational wavelength for even more accurate control. In an embodiment, the periodicity of active unit cells **104** may thus be in an order of 100 nm.

[0101] The optical device **100** may comprise a light shutter structure **120**, which may have an individual shutter **122** associated with each of the subsets **110**, **112** for jointly controlling whether the subset **110**, **112** is active or inactive.

[0102] The light shutter structure **120** may comprise a plurality of shutters **122**, wherein each shutter **122** may be associated with a plurality of unit cells **104** within a single subset **110**, **112**. In some embodiments, a single shutter **122** may be associated with all unit cells **104** of a subset **110**, **112**.

[0103] The light shutter structure **120** may be implemented in many different ways, as will be explained in detail below, and may be active or passive. In particular for a passive light shutter structure **120**, a property of the incident light beam **106** may also be controlled for controlling interaction between the light beam **106** and the light shutter structure **120** and thus defining whether a subset **110**, **112** is active or inactive. For instance, a polarization of the light beam **106** may be controlled.

[0104] Depending on a projection geometry of the optical device **100**, different arrangements for the array **102** of unit cells **104** and a shutter pattern **120** may be required, as illustrated in FIGS. **2***a-b*. FIG. **2***a* illustrates an optical device **100** which is configured to reflect an incident light beam **106** for forming the distribution of the three-dimensional light field, whereas FIG. **2***b* illustrates an optical

device **100** which is configured to transmit an incident light beam **106** for forming the distribution of the three-dimensional light field.

[0105] In the illustrated embodiment of FIGS. **2***a-b*, a pixel pitch of 50 nm of individual unit cells **104** is indicated. With such a pixel pitch, 2×2 unit cells **104** would fit within a square with a 100 nm side. This implies that four subsets **110**, **112**, **114**, **116** of unit cells **104** may be defined in the array **102** of unit cells **104** with each subset **110**, **112**, **114**, **116** having an effective pitch of 100 nm. The unit cells **104** belonging to each subset **110**, **112**, **114**, **116** are illustrated in FIGS. **2***a-b* by different hatchings of the unit cells **104**.

[0106] One subset **110** may be active for forming the distribution of the three-dimensional light field. This is illustrated in FIGS. **2***a-b* by the light shutter structure **120** comprising white areas associated with the active subset **110**, i.e. the light shutter structure **120** allows the incident light beam **106** to reach the unit cells **104** in the active subset **110**. Further, the light shutter structure **120** comprises black areas associated with the inactive subsets **112**, **114**, **116**, i.e. the light shutter structure **120** prevents the incident light beam **106** to reach the unit cells **104** in the inactive subsets **112**, **114**, **116**.

[0107] In the embodiment of FIGS. **2***a-b*, 1 out of 4 pixels are simultaneously activated, and the optical device **100** is illustrated at a given point in time when the subset **110** is active. The unit cells **104** of the inactive subsets **112**, **114**, **116**, are being written at that time to encode the distribution of the three-dimensional light field of next frame(s).

[0108] It should be realized that, although FIGS. **2***a-b* illustrate an optical device **100** comprising four subsets **110**, **112**, **114**, **116**, other number of subsets may be used in the array **102**, such as two or three subsets.

[0109] In case of reflective geometry (as illustrated in FIG. **2***a*) and transmissive geometry (as illustrated in FIG. **2***b*) for the forming of distribution of the three-dimensional light field, the functionality of the shutter structure **120** should have a different nature. For both geometries, an open shutter structure **120** should transmit (part of) the incident light beam **106**, while a closed shutter structure **120** should at least partially prevent transmitting of light.

[0110] In the reflective geometry of FIG. **2***a*, it is desired that the closed shutter does not reflect any of the incident light, which implies that an absorptive shutter structure **120** would work best. In the transmissive geometry of FIG. **2***b*, the shutter structure **120** could be reflective and/or absorptive in the closed state, since for both reflection and absorption the light shutter structure **120** will not create any interference with the distribution of the three-dimensional light field to be formed by the optical device **100**.

[0111] It should also be noted that in the transmissive geometry of FIG. **2***b*, a position of the array **102** of unit cells **104** and the light shutter structure **120** could also be switched without changing any functionality of the device. That is, the light beam **106** may be incident on the array **102** of unit cells **104**. Light transmitted from the array **102** of unit cells **104** may then be incident on the light shutter structure **120**, whereby the light shutter structure **120** may select whether light is further transmitted for selecting whether a unit cell **104** is allowed to contribute to the forming of the distribution of the three-dimensional light field.

[0112] Thus, in one embodiment, the light shutter structure **120** is arranged in relation to the array **102** of unit cells **104**, and the light shutter structure **120** is controllable for selecting whether incident light on the light shutter structure **120** reaches a unit cell **104** with which the light shutter structure **120** is associated for selecting whether the unit cell **104** is being inactive or being active.

[0113] In another embodiment, the light shutter structure **120** is arranged in relation to the array **102** of unit cells **104**, and the light shutter structure **120** is controllable for selecting whether incident light on the light shutter structure **120** allows light being transmitted by a unit cell **104** to contribute to the forming of the distribution of the three-dimensional light field for selecting whether the unit cell **104** is being inactive or being active.

[0114] In the remainder of this disclosure, different implementations are illustrated for the reflective geometry, but it should be realized that, possibly with appropriate adjustments for the transmissive geometry, these implementations may also be used in the transmissive geometry.

[0115] The shuttering of light may be achieved in different architectures, which will be discussed below in relation to various embodiments. Two embodiments are illustrated in FIGS. **3***a-b*.

[0116] In its simplest implementation (illustrated in FIG. **3***a*), the array **102** of unit cells **104** and a pattern of the light shutter structure **120** have the same density and addressing. Such implementation could in some embodiments use identical components to provide a switchable condition of the optical property in the unit cell **104** and to provide a switching of the light shutter structure **120** to control whether the unit cell **104** is active or inactive.

[0117] In such implementation, the addressing of the light shutter structure **120** would be more simple, since a same operation is to be performed on all light shutters associated with a subset **110**, **112**, **114**, **116**.

[0118] A variation on the implementation of the light shutter structure **120** in FIG. **3***a* is shown in FIG. **3***b*, where two subsets **110**, **112** are defined such that 1 out of 2 unit cells **104** are active simultaneously. The subsets **110**, **112** are arranged in a checkerboard pattern, in which the effective pitch of the subsets **110**, **112** is only increased by a factor of $\sqrt{2}$ in relation to the pitch of unit cells **104** in the array **102**. In this geometry, the light shutters **122** can be addressed by simple line electrodes, which simplifies the addressing of the light shutter structure **120** compared to the embodiment in FIG. **3***a*, where there would be a need for cross-point addressing.

[0119] Other implementations of light shutter structures **120** are illustrated in FIGS. **4***a-d*, where the effective pitch of the subsets **110**, **112**, **114**, **116** is increased at least in one dimension (rows/columns), depending on the implementation.

[0120] In the embodiment illustrated in FIG. **4***a*, each column of unit cells **104** in the array **102** share an elongated shutter **122**. Such a pattern allows to control the shutters **122** by means of simple line electrodes. Variations where the shutters **122** cover multiple columns would benefit from the same simple addressing with less stringent limitations to the contact electrodes.

[0121] In the embodiments illustrated in FIGS. **4***b* and **4***c*, there are provided shutters **122** that cover clusters of 2×2 unit cells **104**. The embodiment in FIG. **4***b* defines two subsets **110**, **112** of the array **102**, wherein 1 out of 2 clusters of unit cells **104** are simultaneously active. The embodiment in FIG. **4***c* defines four subsets **110**, **112**, **114**, **116**, wherein 1 out of 4 clusters of unit cells **104** are simultaneously active.

[0122] The embodiment in FIG. **4***b* again allows a very simple contacting of the light shutter structure **120** by means of line electrodes. In the embodiment in FIG. **4***c*, a main advantage is a reduced density in the electrodes required for controlling the light shutter structure **120** (compared to the embodiment in FIG. **3***a*).

[0123] It should be realized that variations on the embodiments illustrated in FIGS. **4***a-c,* where the shutters **122** cover N×M rows and columns would allow reducing complexity of the control electrodes for the light shutter structure **120**, while still maintaining a small pitch of unit cells **104** in the active subset **110** that forms the distribution of the three-dimensional light field.

[0124] The segmentation or arrangement of the unit cells **104** in the active subset **110** will impact calculation of the condition of the optical property to be set for the respective unit cells **104** in order to form the desired distribution of the three-dimensional light field. Also, the segmentation or arrangement of the unit cells **104** in the active subset **110** may affect the image quality that can be attained. Therefore, there may be a trade-off to be made between the image quality and the degree of segmentation of the unit cells **104** in the subsets **110**, **112**, **114**, **116**, both for finding a most practical implementation of the electrodes for controlling the light shutter structure **120** and a most efficient calculation of the desired distribution of the three-dimensional light field.

[0125] In FIG. **4***d*, an embodiment is illustrated where the segmentation of the subsets **110**, **112**, **114**, **116** is done side-by-side. Each subset **110**, **112**, **114**, **116** may be formed in a separate chip, wherein the chips may be arranged in close relation to each other. Thus, each subset **110**, **112**, **114**, **116** may form a sub-array of unit cells **104**. In the embodiment in FIG. **4***d*, an array of 2×2 sub-arrays is used for sequential forming of different distributions of the three-dimensional light field.

[0126] The embodiments above generally describe a light shutter structure **120** which may be applied for a single operational wavelength, i.e. that a single light beam **106** of a single wavelength is incident on the optical device **100**. However, in many applications, such as for an actual display of holographic video, there may be a need for use of multiple colors.

[0127] As such, the segmentation schemes illustrated above can be extended for multiple color operation. Multiple color operation may call for adding color filters to the optical device **100**. The color filters **130** may for instance be integrated on a substrate on which the array **102** of unit cells **104** is formed. A color filter **130** may be arranged to be associated with a single unit cell **104**, such that each unit cell **104** may be associated with a respective color filter for controlling an operational wavelength that will be received by the unit cell **104**

[0128] Additionally or alternatively, the illumination can be masked to selectively illuminate specific areas of the array **102** of unit cells **104** with a specific color.

[0129] Again, choices made for segmentation of the subsets **110**, **112**, **114**, **116** in combination with color filters **130** could have an extra impact on an algorithm for calculation of the condition of the optical property to be set for the respective unit cells **104** in order to form the desired distribution of the three-dimensional light field for different colors. To this extent, it is likely that larger segmentation areas covered by an individual shutter **122** would have less impact on the calculation and again an optimum may be sought in terms of the segmentation that is most practical in terms of implementation both with respect to the algorithm complexity and the required image quality.

[0130] Two embodiments of possible layouts of color filters **130** associated with the array **102** of unit cells **104** are illustrated in FIGS. **5***a-b.* The color filters **130** are illustrated in FIGS. **5***a-b* using a lined hatch pattern to illustrate a color filter **130** allowing blue light to be transmitted, a dotted hatch pattern to illustrate a color filter **130** allowing green light to be transmitted, and a cross-line hatch pattern to illustrate a color filter **130** allowing red light to be transmitted.

[0131] The embodiment in FIG. **5***a* has defined the same number of unit cells **104** for the three target colors red, green and blue, while the embodiment in FIG. **5***b* illustrates use of the YUV color encoding system, which is commonly used in display and camera applications. In the embodiment in FIG. **5***b*, there are twice as many unit cells **104** for green light compared to red and blue, while the arrangement of the color filters **130** still appear in a periodic array. The periodicity of red and blue unit cells **104** is twice the individual pitch of unit cells **104** in the array **102**, while the periodicity of the green unit cells **104** is $\sqrt{2}$ times the individual pitch of unit cells **104** in the array **102**. For applications of displaying holographic images, such a tiling could be used to compensate for different diffraction efficiencies of the switchable unit cells **104** that target the different colors.

[0132] For different tiling schemes, different light shutter structures **120** would be required in order to obtain the desired distribution of the three-dimensional light field and the calculation algorithm will need to account for the segmentation when calculating the condition of the optical property to be set for the respective unit cells **104** in order to form the desired distribution of the three-dimensional light field.

[0133] It is easy to realize that in implementations of FIG. **5***a* and FIG. **5***b*, shutters **122** covering (multiples of) 2×2 and 3×3 arrays (examples indicated by dashed lines in FIGS. **5***a-b*) result in identical geometries of unit cells **104** associated with the respective colors below each shutter **122**.

[0134] In a practical implementation, a tiling as illustrated in FIG. **5***b* may result in a simplified calculation for calculating the condition of the optical property to be set for the respective unit cells **104** compared to the tiling illustrated in FIG. **5***a*, as in the case of FIG. **5***b*, the periodicity of unit cells **104** associated with a specific color is fixed and the individual unit cells **104** are on a square lattice.

[0135] In the embodiment illustrated in FIG. **5***b*, red and blue unit cells **104** are arranged on a square grid with 2 times the period of individual unit cells **104**, while the green unit cells are on a 45 degree rotated square grid with $\sqrt{2}$ times the period of individual unit cells **104**.

[0136] In other embodiments, it could be useful to group clusters of N×M unit cells **104** targeting the same color and arranged in similar patterns as shown in FIGS. **5***a-b,* but where each "pixel" would be a "macro-pixel" consisting of an array of "micro-pixels" (individual unit cells **104**) targeting a specific wavelength. Such a macro-pixel could then be equipped with a single color filter **130**, while the light shutters **122** could again be associated with multiple macro-pixels operating for different colors.

[0137] The color filters **130** may be simple dielectric multilayer bandpass filters that can either be integrated into a substrate on which the array **102** of unit cells **104** is

formed. Alternatively, the color filters **130** with the desired patterning may be placed in front of a light source or anywhere in a light path between the light source and the optical device **100**. In such case, it will be important to have good alignment control to ensure that the color filters **130** are associated with intended unit cells **104**.

[0138] Many different types of light shutter structures **120** could be used, depending on the specific architecture used.

[0139] In a simple case, the light shutter structure **120** used is implemented at unit cell level and a same type of switchable component is used both in the unit cell layer and the light shutter layer, irrespective of the operational mechanism. In such implementation, a good on/off ratio in terms of reflected/transmitted intensity from the light shutter **122** may be needed.

[0140] The use of the same type of switchable component for the light shutter structure **120** and the unit cells **104** would work well in the transmissive geometry (FIG. **2***b*), where an open shutter **122** would be in the same state as a unit cell **104** in an "on"-state (i.e. setting the condition of the optical property to provide a high degree of transmission of light), while a closed shutter **122** would be in the same state as a unit cell **104** in an "off"-state (i.e. setting the condition of the optical property to substantially prevent transmission of light). For such implementation, the transmitted intensity in the on/open state may need to be very large in order to have sufficient light intensity out of the optical device **100**, after light has passed through the unit cell **104** and the light shutter **122**.

[0141] In the reflective geometry (FIG. **2***a*), light passes the shutter **122** twice, when incident on the shutter **122** from the light source and passed to the unit cell **104** and when reflected by the unit cell **104** and passed by the shutter **122** for forming the distribution of the three-dimensional light field above the shutter **122**. Thus, the shutter **122** should again be very transmissive in the open state, while being highly absorptive in the closed state.

[0142] In the open state, the main modulation in the light intensity should come from the unit cell **104** with which the light shutter **122** is associated. In the closed state, the light should be absorbed as to not generate reflections that would interfere with the three-dimensional light field being formed by neighboring active unit cells **104**. For the unit cells **104** on the other hand, a large reflection is desired in the "on"-state, while in the "off"-state the light could either be absorbed or transmitted towards the substrate on which the unit cells **104** are formed.

[0143] Given that the periodicity of the unit cells **104** in a subset **110**, **112**, **114**, **116** may advantageously be well below the operational wavelength, the shutters **122** may be arranged to be associated with a plurality of unit cells **104** in order to avoid a need of the individual shutters **122** to be of a very small size. Such arrangement of the light shutters **122** may at least be used for operational wavelengths in the visible or NIR spectral region (for longer wavelengths, size of unit cells **104** may be larger and the light shutters **122** may be more easily individually formed for respective unit cells **104**). Therefore, the shutters **122** can be larger than the unit cells **104** and be associated with a plurality of unit cells **104**.

[0144] Determining an appropriate dimension for a shutter **122** may involve taking into account an impact of the light shutter **122** on the calculation algorithm for generating a desired distribution of the three-dimensional light field and taking into account practical considerations for the implementation for the shutter **122** based on a shutter type that is selected.

[0145] Below a plurality of different manners of implementing the light shutter structure will be described.

[0146] As described above, PCMs may be useful in controlling a condition of an optical property of a unit cell **104**. For a transmissive geometry, a similar design may be used as a light shutter **122**, at least when the transmitted intensity is sufficiently high.

[0147] Thus, the light shutter **122** may comprise a PCM layer, which may be switched between a first state and a second state, wherein switching of the PCM between the first state and the second state is configured to switch the light shutter **122** between an open state and a closed state.

[0148] The PCM may be configured to switch between a crystalline state and an amorphous state. However, it should be realized that the first and second states may be other configurations of states of the PCM. For instance, the PCM may be configured to switch between two different crystalline states.

[0149] The light shutter **122** may comprise a layer of PCM, which may be combined with other materials, e.g. in a stack of layers of materials, such that the combination of materials may define an open or a closed state of the light shutter **122**. The switching of a state of the PCM may then affect the optical property of, for instance, the stack of layers in the light shutter **122**, such that a state of the light shutter **122** may be controlled by a state of the PCM.

[0150] As outlined above, for reflection-based geometries the functionality of the light shutter **122** and the unit cell **104** would be different. Thus, if the light shutter **122** would be implemented using a PCM in a reflection-based geometry, a design of the light shutter **122** using the PCM (e.g. a stack of layers including the PCM layer) would have to be different from a design of the unit cell **104** using the PCM.

[0151] According to another embodiment, the light shutter structure **120** may use liquid crystals.

[0152] Operation of liquid crystals relies on rotating a linear polarization of light passing through the liquid crystal, which is positioned between two linear polarizers that are rotated 90° with respect to each other. In the open state of the light shutter **122** using a liquid crystal, polarization of light is rotated by 90° in the liquid crystal and therefore light is allowed to be transmitted through the linear polarizers of the light shutter **122**. In the closed state of the light shutter **122**, light maintains the initial polarization when propagated in the liquid crystal and is therefore not allowed to be transmitted through the linear polarizers of the light shutter **122**.

[0153] While technology using liquid crystals is very mature, presently a smallest pixel size that can be realized with liquid crystals is limited to a few microns in size. The rotation of the polarization is achieved by elongated molecules that form a spiral arrangement and that need to physically be rotated and have sufficient interaction with the light to perform well. This implies that for the array **102** of unit cells **104** with sub-wavelength pixel pitch, light shutters **122** using liquid crystals could be applied only on larger blocks of pixels or "macro"-pixels.

[0154] According to another embodiment, the light shutter structure **120** may use an electro-optic effect.

[0155] An electro-optic effect is a change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of light. The

most common changes are a change in the material absorption or in the refractive index or permittivity of the material as function of an external electric field. Both mechanisms can be used to create light shutters **122**, relying on a variety of underlying effects.

[0156] For instance, light shutters **122** may be implements using materials that exhibit a strong electro-optic effect in changing the refractive index using the Pockels effect (linear electro-optic coefficient) or Kerr effect (quadratic electro-optic coefficient). The Pockels effect can be observed in certain crystalline materials that lack inversion symmetry and is in general much stronger than the Kerr effect. The Pockels effect has been widely studied for electro-optic modulators which can be used to change both phase and amplitude of an electromagnetic wave.

[0157] The light shutter **122** may thus be switched between an open and a closed state based on applying a local electric field to the light shutter **122**.

[0158] According to another embodiment, the light shutter structure **120** may use a magneto-optic effect.

[0159] A magneto-optic effect is a change in the optical properties of a material in response to its magnetization. When a material is magnetized, the time-reversal symmetry is broken, which results in off-diagonal terms in a permittivity tensor of the material. When light interacts with such materials, upon transmission or reflection from the material, the polarization state of light is altered, resulting in a modulation of the intensity and phase of light. In a transmission geometry this effect is called the Faraday effect, while in reflection it is called the Magneto-Optical Kerr effect (MOKE). The most common use of these effects is in optical isolators, where a so-called Faraday rotator is used in combination with two linear polarizers. Upon propagating with linearly polarized light through a Faraday rotator, the polarization of light is rotated with an angle that depends on the magnetization of the material, as illustrated in FIG. **6**.

[0160] In a typical optical isolator, the length d is chosen such that the rotation angle β reaches 45°, such that light with vertical polarization allowed to be passed by a first polarizer on an input side will pass through a second polarizer at an output side, wherein the second polarizer is rotated 45° with respect to the first polarizer. If light propagates in an opposite direction from the output side to the input side, the Faraday rotator will give the light a horizontal polarization at the input side, and hence no light will be transmitted through the first polarizer. Upon switching the magnetization of the Faraday rotator, the rotation direction will be reversed, which means that such a device can operate as an optical shutter.

[0161] However, typical rotation values for state-of-the-art garnet-based Faraday rotators is of the order of 0.1°/μm, which means that the propagation length should be fairly long. Thus, a light shutter **122** based on a Faraday rotator may be relatively large. However, it may not be necessary to use a full 45° rotation in the Faraday rotator, so by working with different polarizer angles it may still be possible to realize more compact light shutters **122**, but with a penalty in transmitted power intensity.

[0162] The light shutter **122** using a magneto-optic effect may thus be switched between an open and a closed state based on applying a local magnetic field to the light shutter **122**.

[0163] According to another embodiment, the light shutter structure **120** may use a microelectromechanical system (MEMS) or nano-microelectromechanical system (NEMS) based component.

[0164] MEMS-based components have been used for different types of display devices. Most work is based on micro-mirror arrays that are mainly (but not exclusively) used for reflective projection displays, but also transmissive displays with LED backlighting have been realized with shutter sizes as small as 10 μm. For a transmissive geometry of the MEMS-based component, using MEMS shutters is likely to be very complex, but micro-mirrors could be used as an effective way for illuminating selected parts of the array **102** of unit cells **104**, as illustrated in FIG. **7**.

[0165] The configuration shown in FIG. **7** would work both for reflective geometry and transmissive geometry of the optical device **100**. The MEMS-based light shutter structure **120** comprises an array of micro-mirrors **122**, wherein each micro-mirror may be associated with one or more unit cells **104** in the array **102**.

[0166] Such a MEMS based mirror system may be fabricated with dimensions down to a few μm, so micro-mirrors controlled by a MEMS-based structure may perform a light shuttering that allows to define subsets **110**, **112**, **114**, **116** in the array **102**. The MEMS based mirror system may not be able to select a single unit cell **104** to receive light. Rather, the pixels indicated in FIG. **7** each represent a cluster of unit cells **104** and not individual unit cells **104**. For instance, for a mirror size of 5 μm and a pitch of individual unit cells **104** of 50 nm, a light shutter structure **120** using MEMS based mirror system would be segmenting light into macro-pixels that contain 100×100 individual unit cells **104**.

[0167] The MEMS based mirror system would also be possible to multiplex to multiple colors by equipping each mirror **122** with a bandpass filter that only transmits the target wavelength of the macro-pixel it is illuminating, as illustrated in FIG. **8**.

[0168] The light shutter **122** using a MEMS based mirror system may be switched between an open and a closed state based on controlling a microelectromechanical activator associated with the micro-mirror **122** for setting the micro-mirror in a position to reflect light towards the array **102** of unit cells **104** or direct light into another direction so that it will not reach the array **102**.

[0169] According to another embodiment, the light shutter structure **120** may use passive light polarizers.

[0170] A simple implementation to define two subsets **110**, **112** of unit cells **104** (for a single operational wavelength) would be to equip each subset **110**, **112** with passive (wire-grid) linear polarizers, wherein the polarizers of the respective subsets **110**, **112** are oriented orthogonal with respect to each other.

[0171] A control whether a subset **110**, **112** will be active may then be performed by changing the linear polarization state of the incident light beam **106**. This could be achieved in many different ways, for example by rotating a linear polarizer, photo-elastic modulators (PEMs), liquid crystals or Faraday rotators, which may be associated with the light source or with the optical device **100**.

[0172] According to another embodiment, the light shutter structure **120** may use active light polarizers.

[0173] An architecture with switchable, PCM-based (wire-grid) polarizers could be used to select whether a subset **110**, **112** is active or inactive. In such implementation,

the periodicity and duty cycle of the wire-grid polarizer should be selected as to transmit a lot of light in one state of the PCM and absorb or reflect a lot of light in the other state of the PCM. In such configuration, a subset of unit cells **104** targeting a first color can already be switched on or off using a single linear polarization state for the illumination. A second subset of unit cells **104** targeting another wavelength could then be equipped with switchable polarizers that are rotated 90° with respect to the polarizers of the first subset. Further, the incident light beam of the second color may also have a linear polarization which is rotated with 90° with respect to the first color.

[0174] According to another embodiment, the light shutter structure **120** may, in an implementation with individual light shutters **122** being associated with fairly large clusters of unit cells **104** or being associated with sub-arrays of the unit cells **104**, use macroscopic mechanical shutters, while designing the mechanical shutters to be switched fast enough to maintain a desired frame rate.

[0175] When the unit cells **104** in the array **102** are made polarization-dependent for providing an optical property of the unit cell **104** (for example to function with two different wavelengths that are illuminating the array **102** with orthogonal linear polarization states), all of the above mentioned light shutter structures **120** that are polarization-based could be used to obtain additional functionalities.

[0176] Referring now to FIG. **9**, a system **200** for forming a distribution of a three-dimensional light field will be discussed.

[0177] The system **200** may comprise the optical device **100** according to any of the above described embodiments. The system **200** may further comprise one or more light sources **202** for providing illumination light of the operational wavelength(s).

[0178] Further, the system **200** may comprise optical component(s) which may be arranged in a path between the light sources **202** and the optical device **100** for ensuring a desired illumination of the array **102** of unit cells **104**

[0179] As mentioned for various embodiments above, the light shutter structure **120** may be integrated with a substrate on which the array **102** of unit cells **104** is formed. Alternatively, the light shutter structure **120** may be separately arranged e.g. in the light path between the light sources **202** and the optical device **100** or mounted in relation to the light sources **202**.

[0180] The system **200** may be implemented in a housing **204** for providing a well-controlled mounting of the light sources **202**, the light shutter structure **120** and the optical device **100** in relation to each other.

[0181] The system **200** may further comprise a controller **210**, which may control one or more functions of the system **200**. A controller **210** may be integrated on a substrate on which the array **102** of unit cells **104** is formed and may provide control of when control signals are to be provided to unit cells **104** for switching a condition of an optical property of the unit cells **104**. Further, the controller **210** may control the light shutter structure **120** for switching a light shutter **122** between an open and a closed state.

[0182] The controller **210** may receive information of a desired holographic image to be displayed and may execute an algorithm for calculating of the condition of the optical property to be set for the respective unit cells **104** in order to form the desired distribution of the three-dimensional light field. Alternatively, the controller **210** may receive information of the conditions of the optical property to be set for the unit cells **104** from an external unit, which may execute the algorithm.

[0183] The controller **210** may also control the light sources **202** for setting a polarization of the light sources **202** and synchronizing the polarization of incident light beam **106** on the optical device **100** with a timing of which subset **110**, **112** of unit cells **104** that is to be active.

[0184] It should be realized that the controller **210** may be implemented as one or more processing units, such as a central processing unit (CPU), which may execute the instructions of one or more computer programs in order to implement functionality of the system **200**.

[0185] The controller **210** may alternatively be implemented as firmware arranged e.g. in an embedded system, or as a specifically designed processing unit, such as an Application-Specific Integrated Circuit (ASIC) or a Field-Programmable Gate Array (FPGA).

[0186] Referring now to FIG. **10**, a method for forming a distribution of a three-dimensional light field will be discussed.

[0187] The method may comprise receiving **302** a light beam incident on an array of unit cells. The method further comprises selecting **304** a first subset of unit cells to be active and a second subset of unit cells to be inactive.

[0188] The unit cells of the active subset may thus together define a distribution of a three-dimensional light field formed by the unit cells receiving the incident light beam.

[0189] The method further comprises individually addressing **306** the unit cells in the second subset of unit cells, while the unit cells in the second subset are inactive, in order to control the optical property of the unit cells to one of at least a first condition of the optical property and a second condition of the optical property. By means of the addressing of the unit cells in the second subset, the second subset of unit cells is programmed for forming a distribution of the three-dimensional light field, which will be formed when the subset is switched to being active.

[0190] The method further comprises jointly switching **308** the first subset of unit cells to be inactive, such that the unit cells of the first subset no longer contribute to the distribution of the three-dimensional light field formed by the optical device.

[0191] The method further comprises jointly switching **310** the second subset of unit cells to be active. Thus, the optical device will, after switching the second subset to be active, form the distribution of the three-dimensional light field that has been programmed in the second subset of unit cells while the subset was inactive.

[0192] In the above the inventive concept has mainly been described with reference to a limited number of examples. However, as is readily appreciated by a person skilled in the art, other examples than the ones disclosed above are equally possible within the scope of the inventive concept, as defined by the appended claims.

1. An optical device for forming a distribution of a three-dimensional light field, said optical device comprising:

an array of unit cells, wherein a unit cell in the array of unit cells is individually addressable for controlling an optical property of the unit cell, wherein addressing of the unit cell is configured to switch the optical property of the unit cell between a first condition of the optical property and a second condition of the optical property;

wherein the unit cells in the array of unit cells are configured to be selectively active or inactive and wherein the array of unit cells comprise at least a first subset of unit cells and a second subset of unit cells, wherein the first subset and the second subset are disjoint, and wherein the unit cells in a subset of unit cells are configured to be jointly switched from being inactive to being active,

wherein the active unit cells are configured to interact with an incident light beam and cooperate in forming the distribution of the three-dimensional light field; and

wherein the optical device is configured to address inactive unit cells for switching the optical property of unit cells when the unit cells are inactive.

2. The optical device according to claim **1**, wherein the unit cells of the first subset are arranged interleaved with the unit cells of the second subset in the array of unit cells.

3. The optical device according to claim **1**, wherein the first subset of unit cells forms a first sub-array of unit cells and the second subset of unit cells forms a second sub-array of unit cells and wherein the first sub-array and the second sub-array are arranged adjacent to each other on a common substrate.

4. The optical device according to claim **1**, wherein each subset of unit cells comprise first unit cells configured to interact with a first wavelength of light and second unit cells configured to interact with a second wavelength of light different from the first wavelength of light.

5. The optical device according to claim **1**, further comprising a light shutter structure arranged in relation to the array of unit cells, wherein the light shutter structure is controllable for selecting whether incident light on the light shutter structure reaches a unit cell with which the light shutter structure is associated for selecting whether the unit cell is being inactive or being active.

6. The optical device according to claim **5**, wherein the light shutter structure comprises a first light shutter which is shared by the first subset of unit cells and a second light shutter which is shared by the second subset of unit cells.

7. The optical device according to claim **5**, wherein the light shutter structure comprises an array of light shutter units, wherein each light shutter unit is associated with a single unit cell, and wherein the light shutter units associated with the first subset are configured to be jointly controlled for switching the unit cells in the first subset from being inactive to being active.

8. The optical device according to claim **5**, wherein the optical device comprises a control unit providing control signals to the light shutter structure, wherein a control signal is configured to control whether incident light on the light shutter structure reaches a unit cell with which the light shutter structure is associated based on changing a state of a phase-change material, changing a state of a liquid crystal for controlling light passing through polarization filters, inducing an electro-optical effect, inducing a magneto-optical effect, changing a polarization of light being transmitted by a polarization filter, activating a movement of an actuator in a microelectromechanical system, or activating a macroscopic mechanical shutter.

9. The optical device according to claim **1**, wherein the optical device comprises a set of passive polarization filters arranged in relation to the array of unit cells, wherein the first subset of unit cells is associated with a first polarization filter configured to transmit light of a first polarization, and wherein the second subset of unit cells is associated with a second polarization filter configured to transmit light of a second polarization different from the first polarization.

10. The optical device according to claim **1**, wherein the unit cells comprise a phase-change material, which may be switched between a first state and a second state, wherein switching of the phase-change material between the first state and the second state is configured to switch the optical property of the unit cell between a first condition of the optical property and a second condition of the optical property.

11. The optical device according to claim **1**, wherein the active unit cells are configured to cooperate in reflecting an incident light beam for forming the distribution of the three-dimensional light field.

12. The optical device according claim **1**, wherein the active unit cells are configured to cooperate in transmitting an incident light beam for forming the distribution of the three-dimensional light field.

13. A system for forming a distribution of a three-dimensional light field, said system comprising:

the optical device according to claim **1**; and

a light source configured to emit a light beam to be incident on the array of unit cells.

14. The system according to claim **13**, further comprising a controller for controlling a polarization of light emitted by the light source.

15. A method for forming a distribution of a three-dimensional light field, said method comprising:

receiving a light beam incident on an array of unit cells;

selecting a first subset of unit cells to be active and a second subset of unit cells to be inactive, wherein the first subset of unit cells is disjoint from the second subset of unit cells;

individually addressing the unit cells in the second subset of unit cells, while the unit cells in the second subset are inactive, in order to control the optical property of the unit cell to one of at least a first condition of the optical property and a second condition of the optical property, wherein the second subset of unit cells is programmed by the individual addressing of the unit cells for forming a distribution of the three-dimensional light field;

jointly switching the first subset of unit cells to be inactive; and

jointly switching the second subset of unit cells to be active for changing the distribution of the three-dimensional light field to the distribution programmed in the second subset of unit cells.

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