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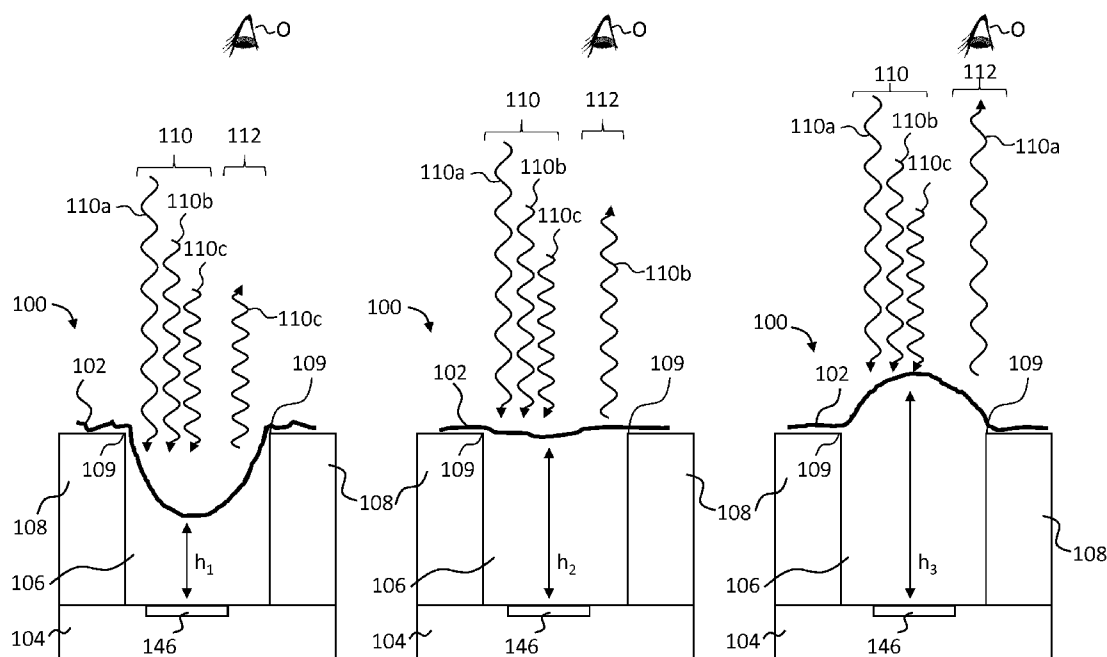


Fig. 1

(57) Abstract: An interferometric modulator device is disclosed that comprises a first flexible layer consisting of one monolayer or two or more stacked monolayers, preferably two stacked monolayers, positioned above a second layer. The first flexible layer and the second layer define a gap of a predetermined height. Further, at least one of the first flexible layer and the second layer is at least partially light transmissive. The device further comprises a conductive element adapted to modify the height of the gap when a voltage is applied across the first flexible layer and the conductive element. A modification of the height causes a modification of the spectrum of light travelling away from the interferometric modulator device.

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Interferometric modulator device comprising a monolayer

FIELD OF THE INVENTION

This disclosure relates to interferometric modulator devices, displays comprising interferometric modulator devices and methods for controlling
5 interferometric modulator devices.

BACKGROUND OF THE INVENTION

Interferometric modulator (IMOD) devices are known that selectively reflect light using principles of optical
10 interference. A known IMOD device, disclosed in WO 2012/030660, includes a pair of reflective layers, a movable reflective layer and a fixed partially reflective layer, positioned at a variable and controllable distance from each other to form an air gap (also referred to as an optical gap
15 or cavity). Incident light that reflects from the two layers can interfere constructively or destructively depending on the position of the movable reflective layer, producing either an overall reflective or non-reflective state for the IMOD device. Such an IMOD device may be used as a pixel in a
20 reflective display as it can be switched between a bright state and a dark state. An IMOD device can also be configured to, in the reflective state, reflect predominantly light of a particular wavelength which allows for a color display.

25 However, the speed with which such IMOD device can switch between two states, the switching speed, is typically low. In fact, the low switching speed of current IMOD devices prevents the use of IMOD technology for video applications. High switching speeds are even more important
30 for virtual reality (VR) or augmented reality (AR) applications that aim to trick a human's brain into thinking that it is receiving real world images.

Another disadvantage of such IMOD device is that it can only be switched between two states, namely a non-reflective and a reflective state, in which reflective state the IMOD device can be controlled to predominantly reflect light of a particular predetermined wavelength. Hence, a single IMOD device cannot produce a continuous color spectrum when it is in the reflective state.

The above IMOD device can be further optimized, not only in terms of switching speed and color control, but also in terms of the amount of power required for switching between two states, in terms of size that a continuous color spectrum device occupies, in terms of data transmission bandwidth when addressing large numbers of devices, and in terms of failure rates.

SUMMARY OF THE INVENTION

It is an object of the present disclosure to provide an improved interferometric modulator device that reduces at least one of the identified drawbacks. An interferometric modulator device may be understood to be a device that selectively absorbs and/or reflects light using the principles of optical interference.

To that end, an interferometric modulator device is disclosed that comprises a first flexible layer consisting of one monolayer or two or more stacked monolayers, preferably two stacked monolayers, positioned above a second layer. The first flexible layer and the second layer define a gap of a predetermined height. Further, at least one of the first flexible layer and the second layer is at least partially light transmissive. The device further comprises a conductive element adapted to modify the height of the gap when a voltage is applied across the first flexible layer and the conductive element. A modification of the height causes a modification of the spectrum of light travelling away from the interferometric modulator device.

A monolayer may comprise an at least partially crystalline structure. The at least partially crystalline structure comprises repetitive units, such as atoms or molecules or ions. The monolayer may be understood to be one repetitive unit thick. A repetitive unit may be the smallest repeating unit in the crystalline structure and a plurality of the repetitive units may form the crystal structure. In a graphene layer, for example, the repetitive unit may be considered to be a carbon atom. The repetitive units may be bonded to each other by means of strong bonds, also called primary bonds. Examples of such strong bonds are covalent bonds, ionic bonds and metallic bonds. The repetitive units may be bonded to each other by a mixture of different types of strong bonds. Each repetitive unit may lack such a strong bond to any particle that is not comprised in the monolayer. The monolayer may thus not be bonded by means of strong bonds to other material. The monolayer may be adhered to other material by means of weak forces, also called secondary forces, such as Van der Waals forces.

Optionally, at least one of the first and second layer, for example the layer that is at least partially light transmissive, is at least partially light absorbent. Optionally, the first layer is at least partially light absorbent. Optionally, the second layer is at least partially light absorbent.

In one embodiment, the first and/or second layer is at least partially light reflective.

The interferometric modulator device controlling said wavelength spectrum may relate to the extent to which the device effectively reflects and/or absorbs various wavelengths of light. For a first gap height, the device may effectively reflect light of a first wavelength and effectively absorb light of a second wavelength, whereas for a second gap height, the device may effectively reflect light of the second wavelength and effectively absorb light of the first wavelength. The interferometric modulator

device thus enables to control a spectrum of light radiating from the interferometric modulator device. Spectrum of light may refer to a distribution of light intensity and/or power over a range of wavelengths. In particular, the

5 interferometric modulator device enables to change the spectrum of light radiating from the device from a first to a second spectrum, wherein the first spectrum may comprise a first dominant wavelength, or a first dominant wavelength range, and the second spectrum may comprise a second
10 dominant wavelength, or second dominant wavelength range. In another example, controlling the wavelength spectrum of light may comprise switching the device from a "dark" state, wherein said spectrum does not comprise any substantial light intensity for any wavelength in the visible, to a
15 state wherein said spectrum comprises a light intensity for only one predetermined wavelength of light, which may occur in two-state interferometric modulator devices.

Changing the gap height may influence the wavelength spectrum of light travelling away from the
20 interferometric modulator device as follows. A change of the gap height may namely cause a change in an interference process, wherein light reflecting from the first layer interferes with light reflecting from the second layer. Depending on this interference process some wavelengths will
25 interfere destructively, which means that light of these wavelengths will to a lesser extent travel away from the interferometric modulator device and may thus be effectively absorbed by the device, whereas other wavelengths will interfere constructively, which means that light of these
30 wavelengths will travel away from the interferometric modulator device and are thus effectively reflected by the device.

The gap height may further influence the interference process as follows. If light having a
35 wavelength λ is incident on one of the layers, e.g. the second layer, it may reflect and interfere with itself to

create a standing wave with local intensity peaks and nulls, wherein the first null is located $\lambda/2$ away from the reflecting layer and subsequent nulls at $\lambda/2$ intervals, e.g. if the layer is metal. Even if the other layer, e.g. the first layer, is light absorbent, if it is very thin and positioned at a distance $\lambda/2$ from the reflecting layer, this light absorbent layer will absorb very little energy because this other layer is then positioned at a null (associated with low intensity) of the standing wave. Hence, the amount of light reflected by the interferometric modulator device may remain unchanged. However, if this light absorbent layer is positioned at a local intensity peak of said standing wave, the light absorbent layer will absorb substantial energy. As a result, the amount of light reflected by the interferometric modulator device will be reduced.

Whether the interference modulator device reflects light of a certain wavelength thus depends on the gap height. This dependence differs for each wavelength as the position of the nulls of said standing wave depends on the wavelength of incident light.

Monolayers, such as atomic layers, are typically flexible, light-weight and strong and possess optical properties that render the monolayers suitable for use as a flexible layer in an interferometric modulator device.

Since a monolayer is relatively light-weight yet strong, the speed with which a monolayer can be switched between two positions is high. Also, moving such a light-weight monolayer requires relatively little power.

Furthermore, since a monolayer typically is flexible and strong, it can be brought into a plurality of positions with respect to the second layer, which allows to vary the gap height over a broad range, which in turn enables to greatly vary the optical properties of the interferometric modulator device as well. In an example, the interferometric modulator device may be able to selectively reflect wavelengths from a broad range of wavelengths, for

example able to reflect light of any wavelength from the visible spectrum. Note that, since the monolayers are flexible and can thus deform themselves, elements such as MEMS springs are not required for moving the first layer with respect to the second layer, which simplifies fabrication.

Also, since monolayers are strong, failures due to breakage of the first layer may be reduced.

The high switching speed of the IMOD device may enable to use IMOD technology in video applications and even in virtual reality and augmented reality applications. Test results of IMOD devices as claimed have shown refresh rates of higher than 1kHz, which greatly exceeds the required refresh rate for any vision application.

The claimed IMOD device enables to increase the resolution of IMOD based displays. IMOD displays currently on the market employ subpixels, e.g. RGB subpixels, wherein a Red subpixel comprises an IMOD configured to assume either one of a dark state or a red light reflecting state, a Blue subpixel comprises an IMOD configured to assume either one of a dark state or a blue light reflecting state and a Green subpixel comprises an IMOD configured to assume either one of a dark state and a green light reflecting state. However, the mechanical properties of monolayers allow large deformations, which advantageously enables to move the first layer into a plurality of positions with respect to the second layer, wherein each position of the first layer may result in a different color of light, or different color spectrum, radiating from the IMOD device. The technologies disclosed herein thus obviate the need to employ subpixels for emitting light of different colors, which in turn enables to increase the resolution of current IMOD displays by means of reducing the pixel size down to the diffraction limit of visible wavelengths, thus allowing a greater pixel density.

The first and second layer defining a gap between them may form an optical cavity, which optical cavity may be non-hermetic. A depth of the optical cavity may correspond to said gap height. The first layer and the second layer may be oriented substantially parallel, at least when the first layer is in a relaxed position.

In one example, at least one of the monolayers comprises graphene, or any of its oxides, atomic intercalated variations or chemically functionalized derivatives.

In one example, at least one of the monolayers comprises hexagonal boron nitride (h-BN), or any of its oxides, atomic intercalated variations or chemically functionalized derivatives. In one example, the monolayer comprises a transition metal chalcogenide, such as MoS₂, MoSe₂, MoTe₂, WS₂, WSe₂, WTe₂, VSe₂, CrS₂, CrSe₂, BP, or any oxides, atomic intercalated variations or chemically functionalized derivatives of transition metal chalcogenides.

In one embodiment, at least one of the monolayers is a graphene layer. Graphene's material properties are very suitable for enabling to increase switching speed and/or to reduce power consumption and transmission bandwidth of the IMOD and/or to radiate multiple colors of visible light with only one IMOD device and/or to improve failure rates of IMOD devices due to mechanical failure.

Graphene namely has a low mass density, a high electrical and thermal conductivity and is an exceptionally strong material. A light graphene layer can be moved more easily, i.e. can be moved faster and/or can be moved using less power. Further, graphene is a (semi-)metal material which obviates the need to implement additional conductive layers in the first layer in order enable electrical control of the first layer. Graphene's high electrical conductivity allows charged particles to easily accumulate/deplete in the first layer. As a result, a targeted potential difference

between first layer and a conductive element for changing the gap height can be achieved fast, which enables fast control and which further benefits switching speed.

Also, graphene is the strongest (tensile strength of 130 GPa) and stiffest (Young's modulus of 1 TPa) material known. Hence, failure rates due to breaking of the first layer can be greatly reduced. The stiffness of graphene also benefits switching speed.

Further, graphene conveniently absorbs all wavelengths of light evenly, which simplifies the design of the interferometric modulator device.

In one embodiment, the first layer consists of at least two stacked monolayers, for example at least two graphene layers or any other combination of monolayers.

Monolayers can be stacked on top of each other in order to control the optical properties, such as reflectance, absorbance and transmittance, of the first layer, as well as mechanical properties. The two monolayers may be adhered to one another by means of secondary forces, such as Van der Waals forces. In an example, layers of h-BN and/or MoS₂ are stacked on top of a first monolayer. In one example an amorphous material, such as gold is deposited on top of a first monolayer.

The two monolayers may consist of the same material, e.g. two graphene layers. A first layer comprising two monolayers of the same material may be easier to fabricate than a first layer comprising sub-layers of different materials, e.g. a first mechanical sub-layer consisting of a material selected for its mechanical properties and a second reflective sub-layer selected for its optical or electrical properties.

In the context of this disclosure, graphene may be a monolayer of carbon atoms in a honeycomb configuration. Each carbon atom may have a sigma-bond with each of its three neighboring carbon atoms. Graphene may thus be

understood to be a so-called two-dimensional material and may be one atom thick.

As said, two layers of graphene may be stacked on top of each other. The at least two layers may be adhered to each other by means of Van der Waals forces. The at least two layers of graphene may constitute bilayer graphene, also called double-layer graphene. Two layers of graphene may be AB stacked (Bernal stacked), which means that carbon atoms of an upper sheet lie directly over the center of a hexagon in a lower graphene sheet. An example of a method for forming an AB-stacked bilayer graphene is given by Nguyen, V. L. et al, (2016), Wafer-Scale Single-Crystalline AB-Stacked Bilayer Graphene. Adv. Mater., 28: 8177-8183. Additionally or alternatively, the two layers of graphene may be AA stacked, in which the layers are exactly aligned. The two layers of graphene may also be incommensurate, which means that one of the layers may have any angle of misalignment with respect to the other layer.

In one embodiment, the first layer is at least partially light transmissive and the second layer is at least partially light transmissive. When both layers are at least partially transmissive, the IMOD can be a transflective interferometric modulator device, wherein light can enter the gap or optical cavity both through the first layer and through the second layer. A transflective IMOD device may be positioned such that it receives light through one layer from a backlighting system and ambient light through the other layer. Transflective displays are convenient because it allows to implement a backlighting system so that observable light may travel away from the device towards an observer even in low ambient lighting conditions.

In one embodiment, the interferometric modulator device comprises a pressure regulation system configured to change a gas pressure inside of the cavity with respect to a gas pressure outside the cavity in order to move the first

layer with respect to the second layer. The cavity may be hermetically sealed.

In one embodiment, the interferometric modulator device comprises a temperature regulation system that is configured to change a temperature of the first layer in order to move the first layer with respect to the second layer.

The first flexible layer may be electrically conductive. Hence, in one embodiment, the interferometric modulator device comprises a conductive element, wherein the first flexible layer is configured to move with respect to the second layer when a voltage is applied across the first layer and the conductive element due to an electrostatic force generated between the flexible first layer and the conductive element in order to change the gap height. In an example, a voltage source changes a potential difference between the first layer and the conductive element from zero to V_{active} . When the potential difference is zero, the first layer may be in a relaxed position since no forces caused by the potential difference act on the first layer. When the voltage source changes the potential difference, e.g. to V_{active} , the first layer may experience a force caused by the potential difference, which force is sufficient to move the first layer with respect to the second layer, for example from the relaxed position to an activated position, herewith changing the gap height.

Optionally, the second layer comprises said electrode. This is convenient because any forces acting on the first layer caused by a potential difference between the first layer and the second layer may then act substantially in a direction towards and/or away from the second layer. Alternatively or additionally, the second layer may form said electrode, which is convenient since the voltage source then may be simply connected to the second layer. In an example, the second layer comprises a silicon substrate and

the voltage source may thus simply be connected to the silicon substrate.

In one embodiment, the interferometric modulator device comprises a spacer structure for spacing the first layer from the second layer. The second layer may be a substrate layer and the spacer structure may be formed on the substrate layer. The spacer structure may support the first layer. The first layer may be suspended from the spacer structure above the second layer and the IMOD device may thus comprise a suspended graphene structure comprising a suspended (optionally double-layer) graphene layer as the first layer.

In one embodiment, the spacer structure, the first layer and the second layer form an optical cavity. The optical cavity may be of cylindrical and/or prismatic form. The cylindrical and/or prismatic form may thus have bases of any shape. Said bases may for example be polygonal, such as rectangular, such as square, and/or curved, such as circular or elliptical. These different embodiments may yield different orientations of the first layer when the first flexible layer is deflected away or towards the second layer. If the bases would be rectangles, the first layer, when deflected towards or away from the second layer, may be oriented more parallel to the second layer than would be the case if said bases would be circles. A more parallel orientation of the first layer in deflected state is advantageous because it is associated with a more constant gap height across the gap and thus with more constant optical properties across the gap as well. Constant optical properties across the gap are beneficial because it allows the interferometric modulator device to more uniformly control the wavelength spectrum across the interferometric modulator device, which may be desired when the device is to be used as a pixel in a display.

Another aspect of this disclosure relates to an interferometric modulator device that comprises a first

movable layer consisting of one monolayer or two or more stacked monolayers, preferably two stacked monolayers, positioned above a second layer. The first movable layer and the second layer define a gap of a predetermined height.

5 Further, at least one of the first movable layer and the second layer is at least partially light transmissive. The device further comprises a conductive element adapted to modify the height of the gap by applying a voltage across the first movable layer and the conductive element. A
10 modification of the height causes a modification of the spectrum of light travelling away from the interferometric modulator device. The first layer may be movable with respect to the second layer. The first layer may be movable in a direction substantially perpendicular to the first or
15 second layer so that the height of the gap is modified when the first layer moves with respect to the second layer. This interferometric modulator device may comprise any feature of any interferometric modulator device disclosed herein.

Another aspect of this disclosure relates to a
20 display that comprises a plurality of interferometric modulator devices as disclosed herein.

Yet another aspect of this disclosure relates to a method for controlling an interferometric modulator device as disclosed herein. The method comprises moving the first
25 layer with respect to the second layer, for example by deflecting the first layer, to modify a spectrum of light travelling away from the interferometric modulator device. Moving the first layer with respect to the second layer may comprise controlling a voltage source to change a potential
30 difference between the first layer and the conductive element. Light radiating from the interferometric device may be the result of light incident on the interferometric device entering the said gap between the first and second layer through the first and/or second layer. Moving the
35 first layer with respect to the second layer may be performed based on control information.

Both the first and second spectrum of light may comprise visible light so that the interferometric device can subsequently radiate light of different colors, which enables to produce a multi-color pixel for a display. The visible light may be observable, e.g. observable by a person.

Yet another aspect of this disclosure relates to a controller for use in the interferometric modulator device as described herein, the controller being configured to perform one or more of the methods as described herein.

Yet another aspect of this disclosure relates to a computer program or suite of computer programs comprising at least one software code portion or a computer program product storing at least one software code portion, the software code portion, when run on a computer system, being configured for executing one or more of the methods as described herein.

Yet another aspect of this disclosure relates to a non-transitory computer-readable storage medium storing at least one software code portion, the software code portion, when executed or processed by a computer, causing the computer to carry out one or more of the methods as described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the invention will be explained in greater detail by reference to exemplary embodiments shown in the drawings, in which:

FIG. 1 shows an interferometric modulator device according to an embodiment of the invention;

FIGs. 2A and 2B illustrate working principles of the device;

FIG. 3A shows an embodiment wherein the second layer is at least partially light transmissive;

FIG. 3B shows an embodiment wherein both the first and second layer are at least partially light transmissive;

FIG. 4A shows the structural formula of graphene;

FIG. 4B shows the structural formula of hexagonal boron nitride (hBN);

FIG. 4C shows two graphene layers stacked on top
5 of each other;

FIGs. 5A and 5B show simulation results that illustrate the relation between gap height and optical properties of the interferometric modulator device;

FIG. 6 depicts an interferometric modulator device
10 according to an embodiment that comprises means for moving the first layer with respect to the second layer;

FIG. 7 shows a microscopic image of a plurality of interferometric devices according to an embodiment;

FIG. 8 shows different arrangements for a
15 plurality of interferometric devices.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts an interferometric modulator device
100 according to one embodiment of the invention. The device
20 100 comprises a first layer 102 that may be at least partially light reflective and that may be flexible and a second layer 104 that may also be at least partially light reflective. The first layer 102 and/or the second layer 104 may thus have a reflectance larger than 0%. At least one of
25 the first 102 and second 104 layer is at least partially light transmissive. In the embodiment shown, the first layer 102 is at least partially light transmissive. The first 102 and second 104 layer define a gap 106 between them. Further, the first layer 102 is configured to move with respect to
30 the second layer 104 to change a gap height h of the gap in order to change the optical properties of the interferometric modulator device 100.

The second layer may be part of a substrate, e.g. a silicon substrate. In one example, the second layer 104
35 comprises silicon. The first layer 102 may be suspended from a spacer structure 108, e.g. from one or more edges 109 of

the spacer structure 108. The spacer structure may comprise an electrically insulating material, such as SiO₂. The spacer structure may be configured to space the first layer 102 from the second layer 104. The first layer 102 may connect to one or more edges 109 of the spacer structure. The first layer, second layer and the spacer structure 108 may form an optical cavity having a depth corresponding to said gap height.

The device 100 comprises a conductive element 146 adapted to modify the height of the gap when a voltage is applied across the first flexible layer 109 and the conductive element 146, a modification of the height causing a modification of the spectrum of light travelling away from the interferometric modulator device 100.

The first layer 102 consists of at least one monolayer that may comprise an at least partially crystalline structure. The at least partially crystalline structure comprises repetitive units, such as atoms or molecules, and the monolayer may be understood to be one repetitive unit thick. In one example, the first layer 102 comprises a monolayer in the sense that it comprises a graphene layer.

The first layer 102 may be suspended from the spacer structure 108 and the suspended layer 102 may deflect and/or deform to change the height of the optical gap.

The interferometric modulator device 100 may be fabricated using any MEMS (micro-electro-mechanical systems) fabrication technique. The device may for example be fabricated as follows. In a first step an oxide layer is applied to a substrate 104. In an example, a 600 nm thick layer of SiO₂ is thermally grown onto a silicon substrate. In a second step a cavity 106, e.g. a circular cavity or rectangular cavity, is formed by etching through the oxide layer, for example by using reactive ion etching. In a third step, the first layer 102, e.g. a double layer of graphene, is transferred onto the cavity optionally using a semidry

transfer technique. Conveniently this method allows to simultaneously fabricate a plurality of interferometric devices 100, which may be beneficial for the fabrication of a high-resolution display.

5 In one example the interferometric device is fabricated as follows. A single-layer graphene is grown by chemical vapour deposition (CVD) using a 4" cold wall reactor (Aixtron BM). Copper foil is used as the catalyst and a surface pre-treatment is carried out in order to
10 remove the native copper oxide and other impurities. The synthesis is carried out at 1000 °C using methane as the carbon source. After the synthesis, the single-layer graphene is coated with a polymer layer and stacked onto a second single-layer graphene by using a semi-dry transfer
15 process. The stacked double-layer CVD graphene is then transferred onto 20 mm² SiO₂/Si substrates containing circular cavities of 1-20 micrometers in size and 600 nm in depth by following a semi-dry transfer procedure. Finally, the supporting polymer layer is removed by annealing at 450
20 °C for 2 hours in N₂ atmosphere.

FIG. 1 shows the interferometric modulator device in three different states. In each state, the first layer 102 has moved into a different position with respect to the second layer 104 and hence has influenced the gap height h .
25 In one state the interferometric modulator device 100, the gap height is h_1 , in another state h_2 , in yet another state h_3 . Gap height, which may correspond to a distance between the first and second layer, may be understood as an average height of the gap and/or as a characterizing height of the
30 gap.

When the first layer 102 is in a default position or rest position, which may be the position of the first layer 102 when no voltage is applied across the first layer 102 and the conductive element, the gap height may be a
35 default gap height. The default gap height may be in the range 100 - 1000 nm, preferably 300-800 nm, more preferably

400–800 nm. The default gap height may substantially correspond to a depth of a cavity that is etched into a substrate layer, for example as described above.

The gap height may be modifiable such that it varies between 0 nm, corresponding to the first flexible layer 102 touching the second layer 104, and 1000 nm, preferably such that the gap height varies between 100–800 nm, more preferably between 100–400 nm.

The wavelength spectrum of light 112 travelling away from the device 100 depends on the gap height of the gap defined by the first 102 and second 104 layer.

FIG. 1 shows that light 110 is incident on the interferometric modulator 100 and that the incident light 110, which may be ambient light, and which may be white light, e.g. sunlight, may comprise a plurality of wavelengths: a first (long) wavelength 110a, a second wavelength 110b and a third (short) wavelength 110c. In an example, an observer O observes light 112 radiating from, e.g. effectively reflecting from, the device 100. FIG. 1 illustrates that the interferometric modulator device 100, if the gap height of the gap equals h_1 , effectively reflects light having wavelength 110c and to a lesser extent reflects, or effectively absorbs, the wavelengths 110a and 110b. Or in other words, the wavelength spectrum of light 112 travelling away from the device 100 comprises an intensity for wavelength 110c and does not comprise an intensity for wavelength 110a nor 110b. Further, if the gap height equals h_2 , the interferometric modulator device 100 effectively reflects light having wavelength 110b and to a lesser extent reflects, or effectively absorbs, the wavelengths 110a and 110c. If the gap height equals h_3 , the device 100 reflects light having wavelength 110a and to a lesser extent reflects, or effectively absorbs, the wavelengths 110b and 110c. Hence, the gap height influences the wavelengths spectrum of light 112 traveling away from the device 100.

FIGs. 2A and 2B illustrate how the gap height, or the position of the first layer with respect to the second layer, causes the interferometric device 200 to radiate certain wavelengths while absorbing other wavelengths.

FIGs. 2A and 2B show an interferometric modulator device 200 according to one embodiment in a state wherein incident light having wavelength 210a is absorbed by the interferometric device 200. In the drawings, two elements indicated by reference numerals that differ by 100 are similar or identical elements. Both FIG. 2A and 2B show that light is incident on the interferometric device, the light having a wavelength 210a. The light 210a is incident in particular on the first layer 202.

With reference to FIG. 2A, part of light 210a passes through the first layer 202 and hits the second layer 204, which second layer 204 reflects the light back towards and through the first layer 202 yielding reflected light 214a. However, the first layer 202 partially reflects the incident light yielding reflected light 216a. Light thus has entered the gap between the first 202 and second 204 layer and thus light 214a has thus traveled a longer distance than light 216a. The longer distance introduces a phase shift of light 214a with respect to light 216a, which phase shift may result in either constructive or destructive interference between light 216a and light 214a. The phase shift, which determines whether constructive or destructive interference occurs (as indicated by the bold cross), depends on the gap height and on the wavelength of light 210a. As a general rule, if the path length difference is equal to half of the wavelength or equal to an odd multiple of half the wavelength, destructive interference occurs. If said path length difference is equal to an even multiple of half the particular wavelength constructive interference occurs. Hence, a particular gap height may result for light of wavelength 110a in destructive interference, as is depicted in FIG. 2A, whereas this particular gap height may result in

constructive interference for light of wavelength 110b, a situation depicted in FIG. 1.

FIG. 2B further shows that incident light 210a passing through the first layer and reflecting from the second layer 204 may interfere with itself and construct a standing wave, which leads to areas, indicated by the light shaded areas L, associated with low intensities of electromagnetic radiation (light) and to areas, indicated by the dark shaded areas H, associated with high intensities of electromagnetic radiation. If the first layer 202 is positioned in a high intensity area H, the first layer 202 will absorb a substantial amount of the electromagnetic radiation. As a result, constructive interference may occur to a lesser extent.

For a circular interferometric device, wherein the optical cavity has the form of a cylinder having circular bases, and wherein the first layer is a double-layer graphene (DLG) layer, the total reflected intensity for a given wavelength λ at a distance r from the center of the first layer may be approximated by:

$$I(r) = I_g + I_s + 2\sqrt{I_g I_s} \cos\left(\frac{4\pi}{\lambda}(g_0 - \delta(r) + \varphi)\right)$$

, where I_g is intensity of light 216 reflected from the first layer, I_s is intensity of light 214 reflected from the second layer, g_0 is the default gap height, which may correspond to the gap distance between the nondeflected layer (corresponding to the first layer) and the bottom of the cavity (corresponding to the second layer), $\delta(r)$ is the radial deflection, and φ is the phase change induced by the reflecting surfaces.

The reflectance may also be approximated by:

$$R = \left| 2r_1 e^{i\varphi_2} \sin(\varphi_1) + r_2 e^{-(\varphi_1 + \varphi_2)} - \frac{r_1^2 r_2 e^{i(\varphi_1 - \varphi_2)}}{e^{i(\varphi_1 + \varphi_2)} + r_1^2 e^{-i(\varphi_1 - \varphi_2)} + 2r_1 r_2 e^{-i\varphi_2} \sin(\varphi_1)} \right|$$

, wherein $\varphi_1 = \frac{2\pi n_1 t_G}{\lambda}$ and $\varphi_2 = \frac{2\pi h}{\lambda}$.

In these equations, r_1 and r_2 are the Fresnel reflection coefficients of air-graphene and air-silicon interfaces, respectively. ϕ_1 and ϕ_2 are the phase changes induced by the optical path through the graphene and the cavity respectively, t_G is the graphene layer thickness, and λ is the optical wavelength. n_1 is the refractive indices the first layer. h is the gap height.

FIG. 3A shows an embodiment of the interferometric device, wherein the second layer 304 is at least partially transmissive and at least partially light reflective. Incident light 310 comprising a plurality of wavelengths, which light may be ambient light, is incident on the interferometric device 300 and light 312 comprising only a selection of said plurality of wavelengths is reflected from the device 300. In this embodiment, the first layer 302 does not need to be light transmissive. Light can enter and exit through the second layer 304.

FIG. 3B shows an embodiment of an interferometric modulator device 300, wherein both the first and second layer are at least partially transmissive. Light 324, which optionally originates from a backlighting system 322, is incident on the interferometric modulator device 300. The interferometric modulator device 300 may be configured, e.g. positioned, to receive incident light 324 from the backlighting system 322. The backlighting system 322 may be configured to radiate light 324 towards the interferometric modulator device 300. Light 324 may comprise a plurality of wavelengths. One distinct aspect of this disclosure relates to a system comprising an interferometric modulator device as disclosed herein and further comprising a backlighting system as disclosed herein.

Light thus can enter the optical gap through the second layer 304 and exit the optical gap through first layer 302. Hence, this embodiment may be a transflective interferometric modulator device. An observer O may be

present who observes light 312 traveling away from the device 300.

Optionally, the interferometric modulator device 300 shown in FIG. 3B also receives ambient light 310 as shown, so that both ambient light 310 and light 324, optionally originating from a backlighting system, may enter the optical cavity and contribute to the intensity of light 312 that in the end radiates from the interferometric modulator device 300. This embodiment is advantageous because it enables that light 312 may be observable for an observer O even if there is almost no ambient light. In low ambient lighting conditions, the backlighting system may namely be used to increase the brightness of the light 312 radiating from the interferometric modulator device 300. If high levels of ambient lighting are present, the backlighting system 322 may be switched off in order to reduce the power consumption of the interferometric modulator device 300. Such interferometric modulators devices may thus enable to produce energy efficient, transfective displays.

As described above, an observer O that is able to observe light 312 travelling away from the interferometric modulator device, may be positioned on either side of the interferometric modulator device 300, for example on the side of the first layer 302 or on the side of the second layer 304. Light 312 may thus travel away from the device 300 in any direction. In one embodiment, the interferometric modulator device is configured, e.g. positioned, such that light enters the gap 306 (substantially) from only one side of the device 300, for example through the first layer 302 or through the second layer 304. In another embodiment, the device is configured such that light enters the gap 306 from both sides of the device, thus through first layer 302 and through second layer 304.

FIG. 4A illustrates a structural formula of graphene. Carbon atoms may be arranged in a so-called

honeycomb configuration and the carbon atoms may be positioned in one plane. The carbon atoms may be regularly positioned with respect to each other and thus may form a crystalline structure. A layer of graphene may comprise a number of defects, such as structural defects and/or chemical defects. In one example, a number of oxygen atoms occur in the structure in addition to carbon atoms. A layer of graphene in the context of this disclosure may thus be at least partially crystalline.

FIG. 4B shows the structural formula of hexagonal boron nitride.

FIG. 4C shows two layers of graphene, a first layer of graphene 438 and a second layer of graphene 440, that are stacked on top of each other. The structure of FIG. 4C may thus be understood to be a double-layer graphene structure. The two layers of graphene are adhered by means of secondary forces, in this example by Van der Waals forces, indicated by 442. Substantially no covalent bonds between atoms may be present between the two layers of graphene.

FIG. 5A shows results of a simulation, wherein light comprising three wavelengths, 460 nm, 532 nm and 633 nm, is incident on an interferometric modulator device according to one embodiment. For each wavelength, the reflectance is measured, which relates to the intensity of light radiating from the interferometric modulator device. A gap height, corresponding to the air gap, is varied and as a result, for each wavelength, the reflectance also varies.

FIG. 5B schematically shows a simulated first and second light spectrum radiating from the interferometric modulator device. The first spectrum is associated with an optical cavity in a first state, for example an optical cavity having a gap height (air gap) of 400 nm, whereas the second spectrum is associated with the optical cavity in a second state, for example having a gap height of 780 nm.

FIG. 5B is derived from the data shown in FIG. 5A and shows

that the first spectrum comprises a first dominant wavelength, in this example the dominant wavelength of 460 nm, and that the second spectrum comprises a second dominant wavelength, in this example the wavelength of 532 nm.

5 With reference to FIG. 6, in one embodiment of the invention the interferometric modulator device 600 comprises a conductive element 646, wherein the first flexible layer 602 is configured to move with respect to the second layer 604 when a voltage is applied across the first layer and the
10 conductive element due to an electrostatic force generated between the flexible first layer 602 and the conductive element 646 in order to change the gap height.

Optionally, the first layer 602 is further connected to ground potential (not shown).

15 FIG. 7A is a microscopic image of a plurality of interferometric modulator devices according to an embodiment of the invention. The positions of the optical gaps of the plurality of interferometric modulator devices are indicated by 706. Area 708 indicates the presence of the spacer
20 structure, which spacer structure in this example comprises SiO₂. Production of these devices started with a silicon substrate covered with 600 nm of thermally grown SiO₂. Subsequently, circular cavities having a diameter of 10 micrometers were etched through the oxide by means of
25 reactive ion etching. Then a double layer graphene was transferred onto the substrate.

FIG. 7B shows two photographs taken during an experiment from the same subset of IMOD devices 700. Scalebars 750 indicate 10 micrometers. In this experiment
30 this set of IMOD devices 700 was continuously illuminated with white light. The first layer was a double graphene layer, which was connected to a voltage source that applied a varying potential to the double graphene layer. The silicon layer was connected to ground potential.

35 The varying potential difference between the double graphene layer and the silicon layer caused the

double graphene layer to move with respect to the silicon substrate. As a result, the wavelength spectrum of light reflecting from the devices 700 also varied. The top photograph was taken at a first time instant and the bottom photograph at a second time instant. FIG. 7B shows that the color of the light radiating from the devices 700 differs between the two time instants.

FIG. 8 shows a plurality of configurations each configuration comprising a plurality of interferometric modulator devices according to an embodiment. In FIG. 8, the dark grey areas 806 indicate the positions of the gaps of the interferometric modulator devices as defined by first and second layers, whereas the white lines indicate the spacer structure 809, in particular the positions of the edges 809 of the spacer structure to which the first layer is connected. The one or more edges 809 of an interferometric modulator device may form any shape, which shape may correspond to the shape of the bases of a cylindrical and/or prismatic form of the optical cavity as defined by the first layer, the second layer and the spacer structure. Possible shapes of said bases are a circle, a polygon, a square, a triangle, et cetera. The configurations may be used for implementing the interferometric modulator devices in a display.

CLAIMS

1. An interferometric modulator device comprising:
a first flexible layer consisting of one monolayer
or two or more stacked monolayers, preferably two stacked
monolayers, positioned above a second layer, the first
flexible layer and the second layer defining a gap of a
predetermined height;

at least one of the first flexible layer and the
second layer being at least partially light transmissive;
and,

a conductive element adapted to modify the height
of the gap when a voltage is applied across the first
flexible layer and the conductive element, a modification of
the height causing a modification of the spectrum of light
travelling away from the interferometric modulator device.

2. The interferometric modulator device according
to claim 1, wherein the two or more stacked monolayers are
adhered to each other by means of Van der Waals forces.

3. The interferometric modulator device according
to claim 1 or 2, wherein the one monolayer or at least one
of the two or more monolayers comprises graphene, preferably
the one monolayer or at least one of the two or more
monolayers being a graphene monolayer.

4. The interferometric modulator device according
to claim 1, 2 or 3, wherein the one monolayer or at least
one of the two or more monolayers comprises hexagonal boron
nitride.

5. The interferometric modulator device according
to one or more of the preceding claims, wherein the one

monolayer or at least one of the two or more monolayers comprises a transition metal chalcogenide.

6. The interferometric modulator device according to one or more of the preceding claims, wherein the gap height can be modified between 0 and 1000 nm, preferably between 100 and 800 nm, more preferably between 100 and 400 nm.

7. The interferometric modulator device according to one or more of the preceding claims, wherein the first flexible layer is at least partially light transmissive and wherein the second layer is at least partially light transmissive.

8. The interferometric modulator device according to one or more of the preceding claims, wherein the first and/or second layer is at least partially light absorbent.

9. The interferometric modulator device according to one or more of the preceding claims, wherein the first and/or second layer is at least partially light reflective.

10. The interferometric modulator device according to one or more of the preceding claims, wherein the first layer consists of two monolayers, a first monolayer comprising graphene stacked on top of a second monolayer comprising graphene.

11. The interferometric modulator device according to one or more of the preceding claims, further comprising a spacer structure, e.g. formed on the second layer, which optionally is a substrate layer, for spacing the first layer from the second layer.

12. The interferometric modulator device according to claim 11, wherein the first layer is suspended from the spacer structure above the second layer and wherein the spacer structure, the first layer and the second layer form an optical cavity.

13. The interferometric modulator device according to claim 12, wherein the optical cavity is shaped as a cylinder having a curved base, e.g. a circular base, and/or as a prism having a polygonal base, e.g. a rectangular base.

14. The interferometric modulator device according to one or more of the preceding claims, wherein the second layer comprises and/or forms said electrode.

15. A display comprising a plurality of interferometric modulator devices according to one or more of the preceding claims.

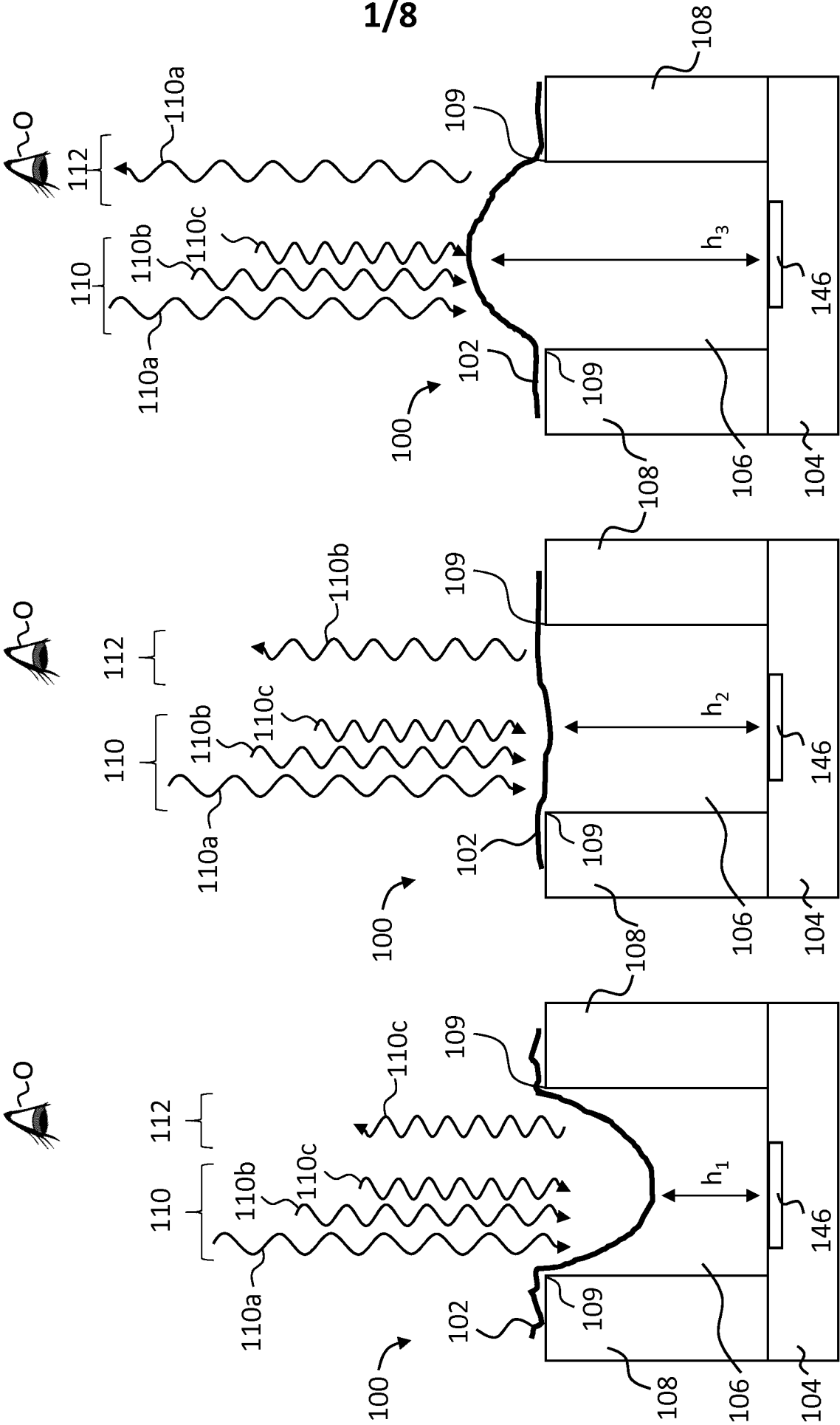


Fig. 1

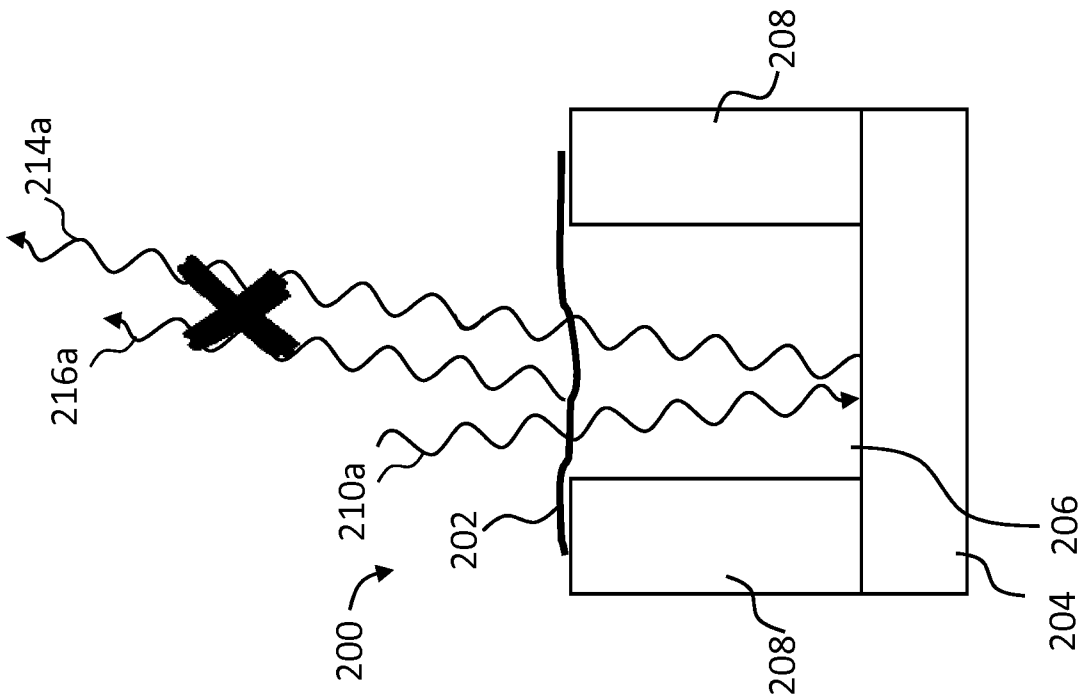


Fig. 2A

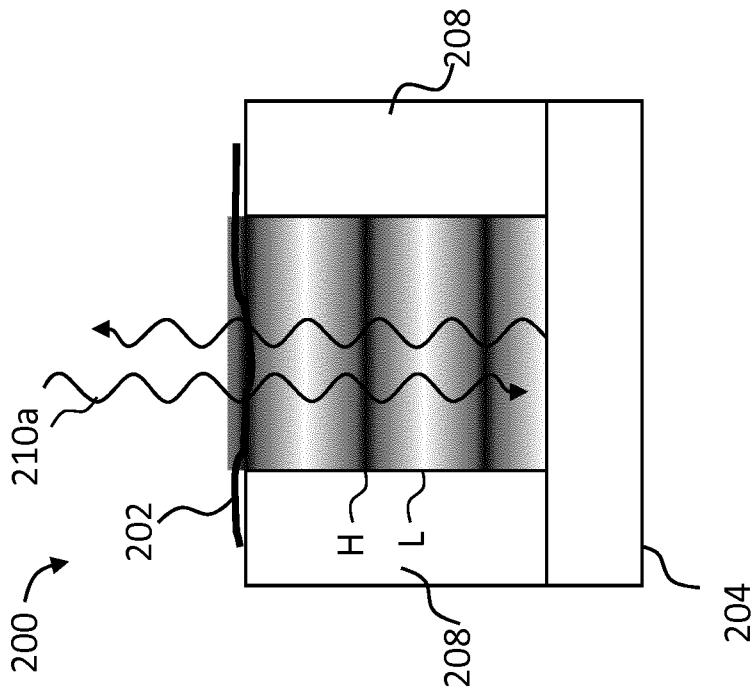
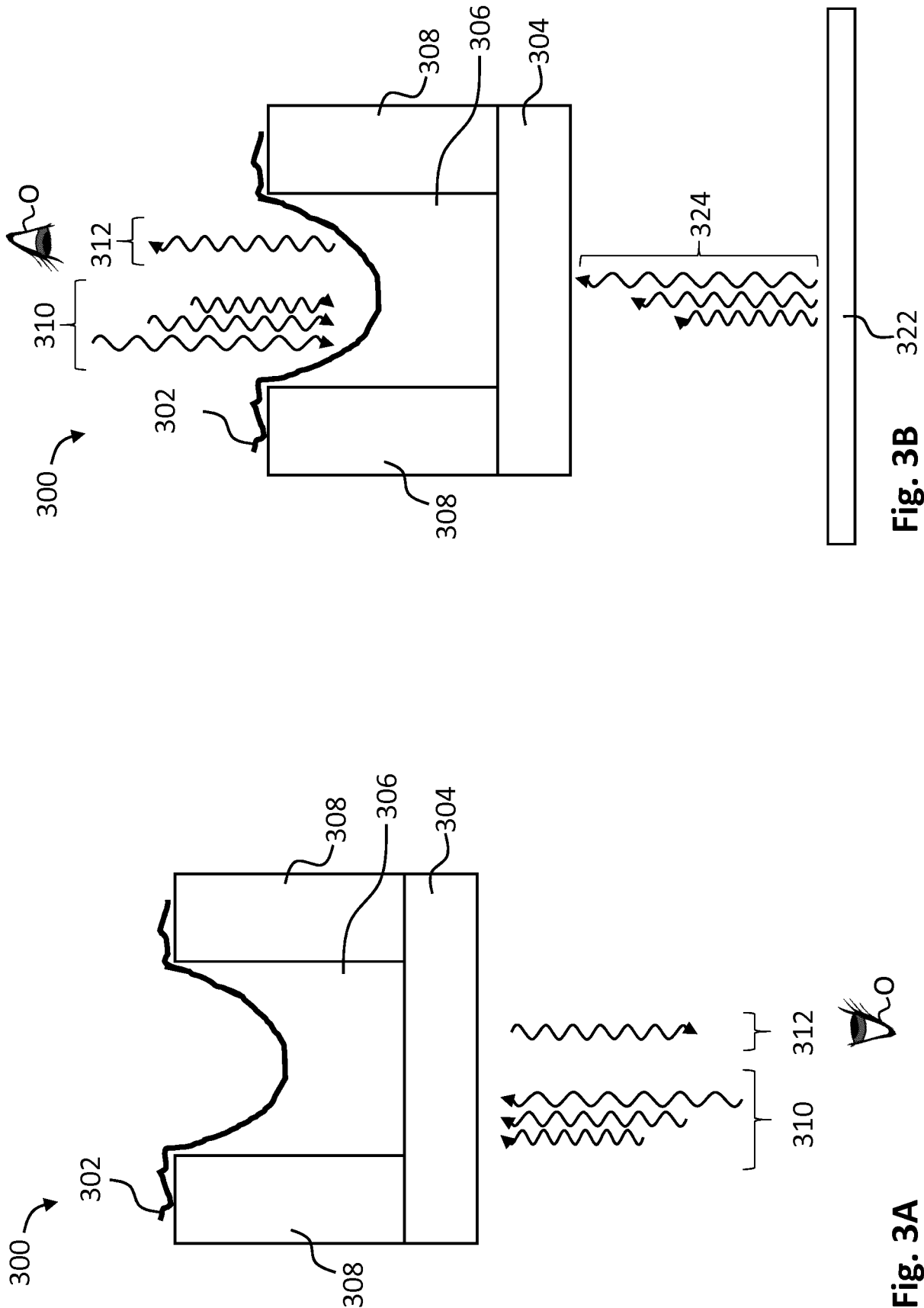


Fig. 2B



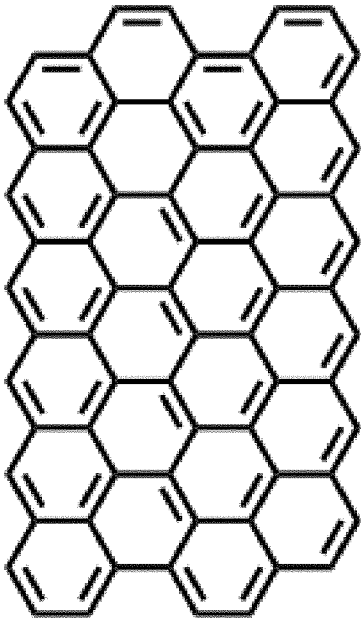


Fig. 4A

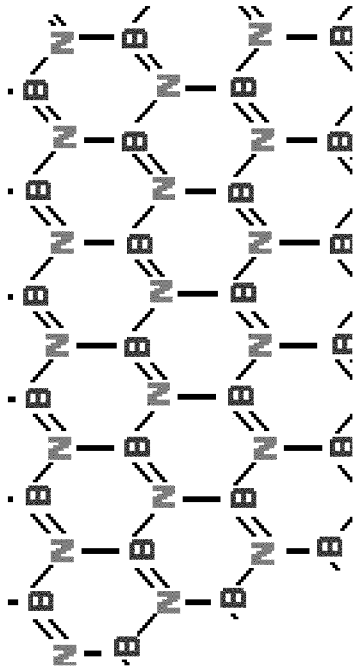
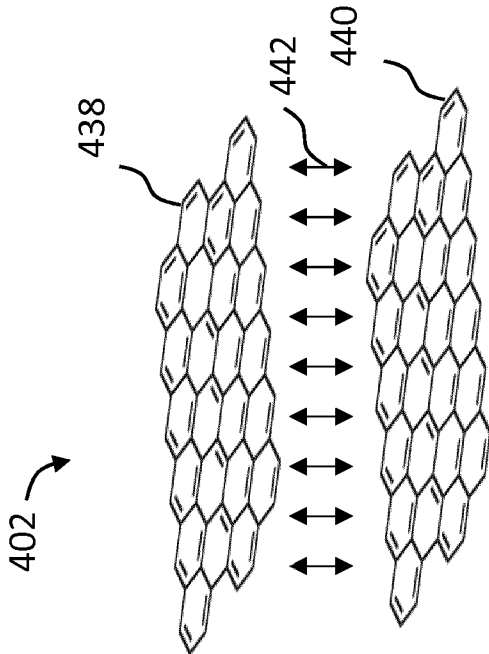


Fig. 4B

Fig. 4C

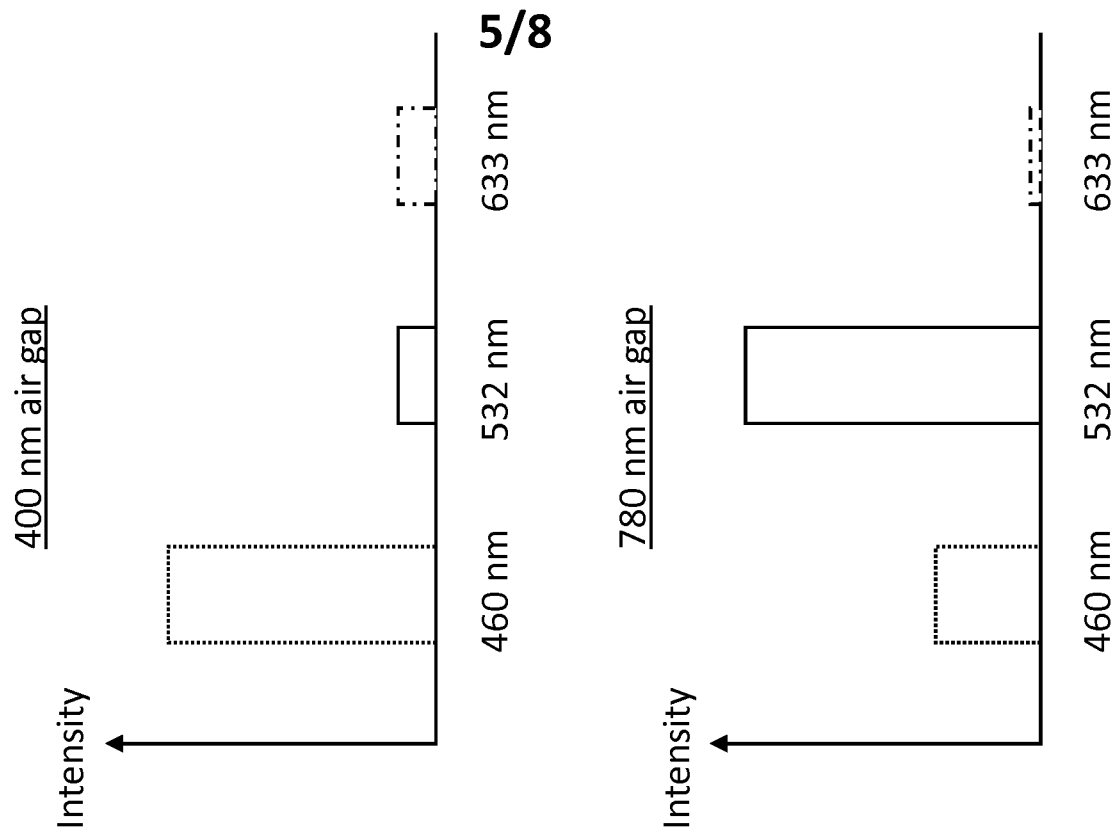


Fig. 5B

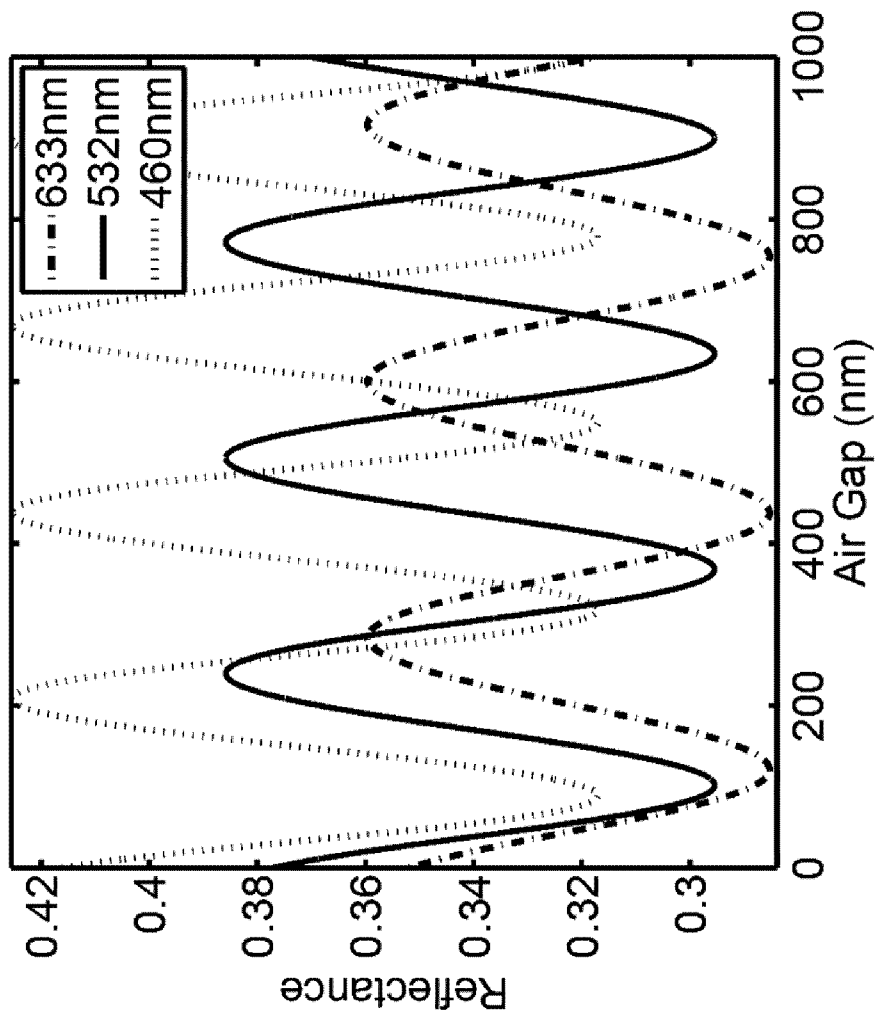


Fig. 5A

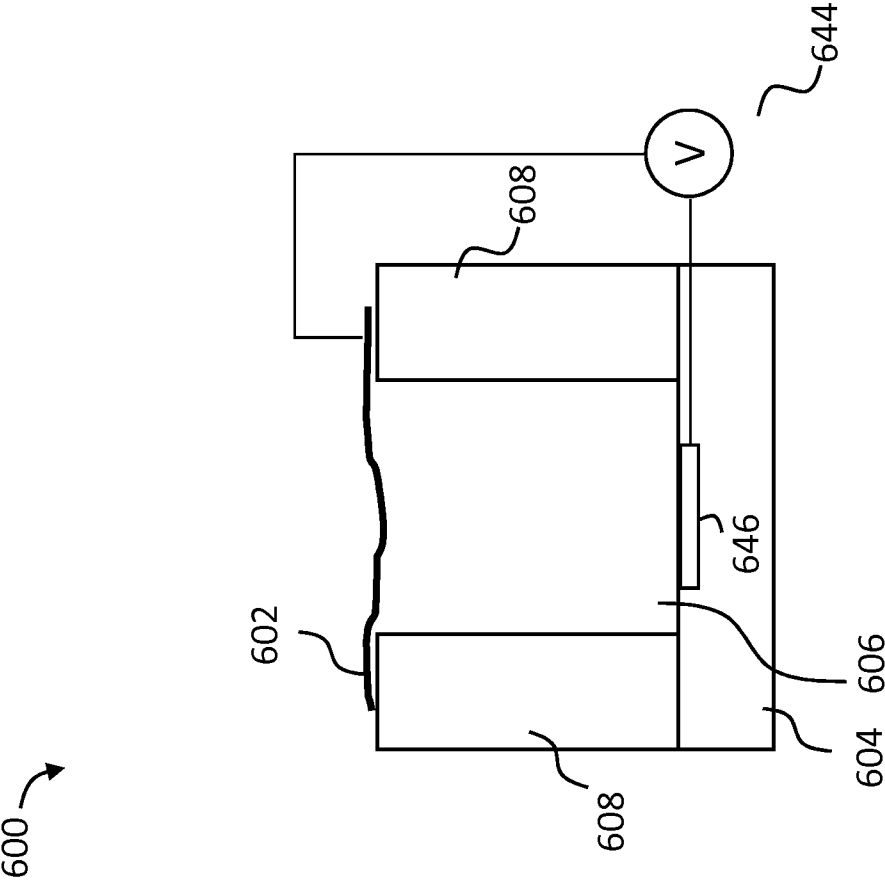


Fig. 6

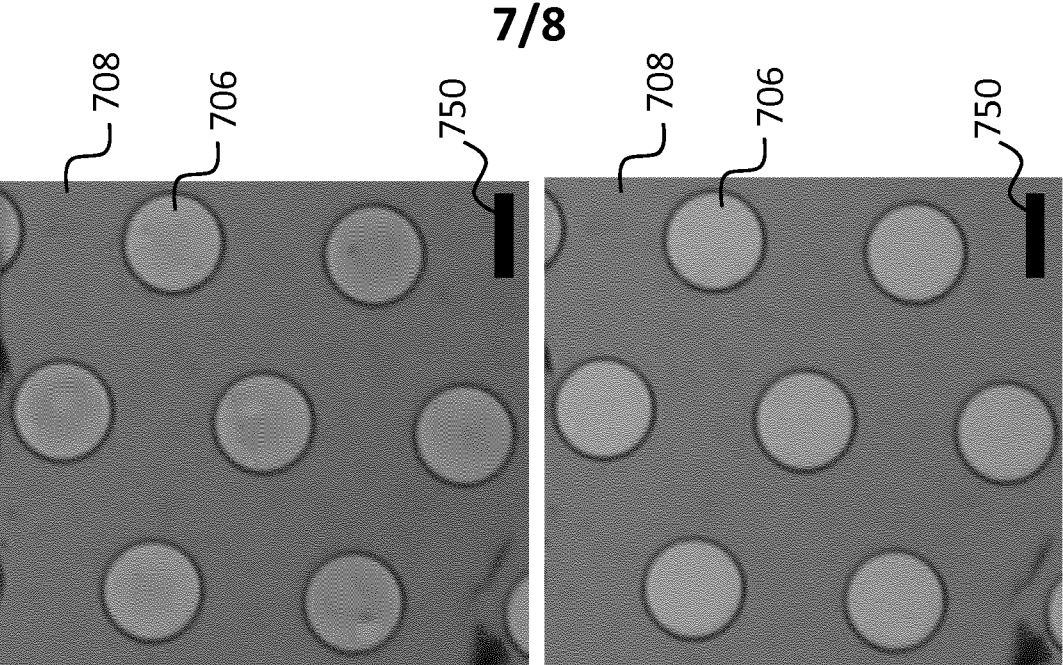


Fig. 7B

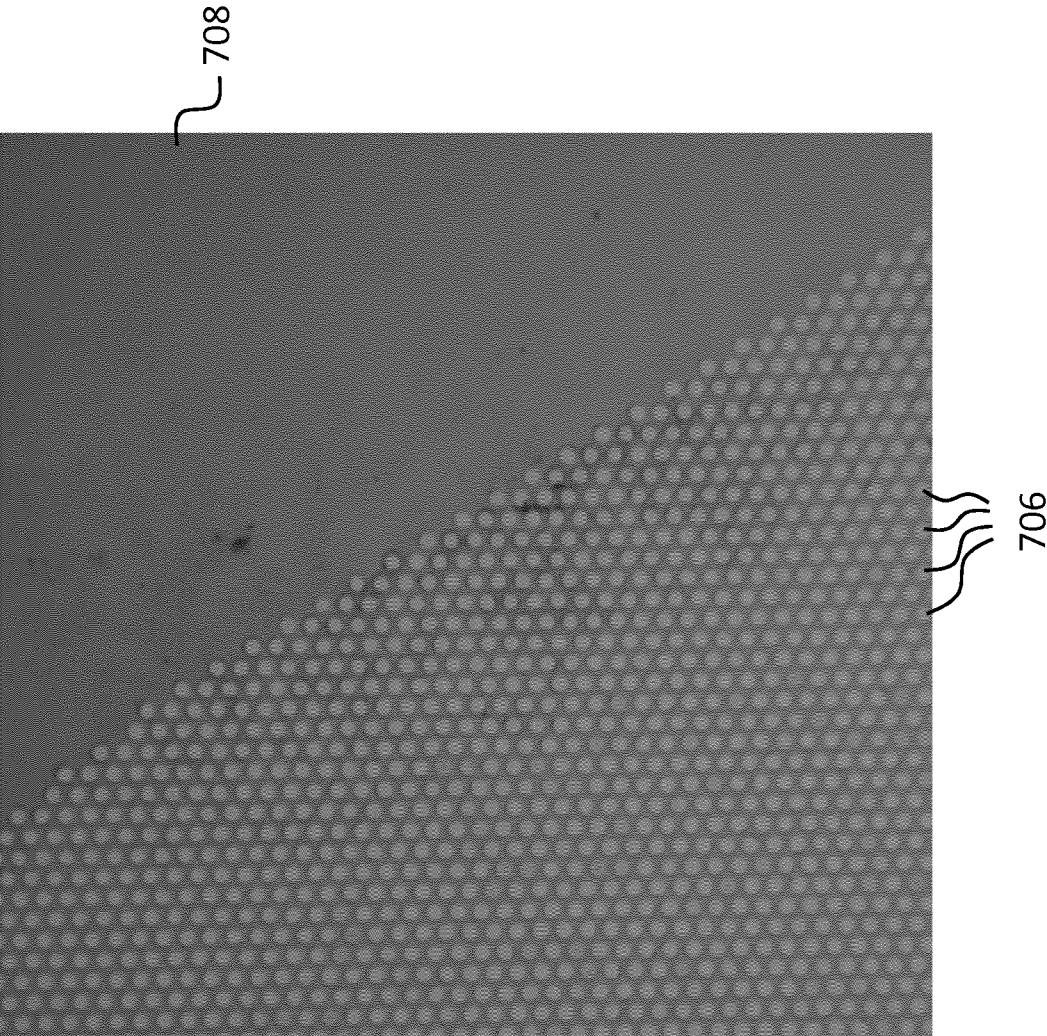


Fig. 7A

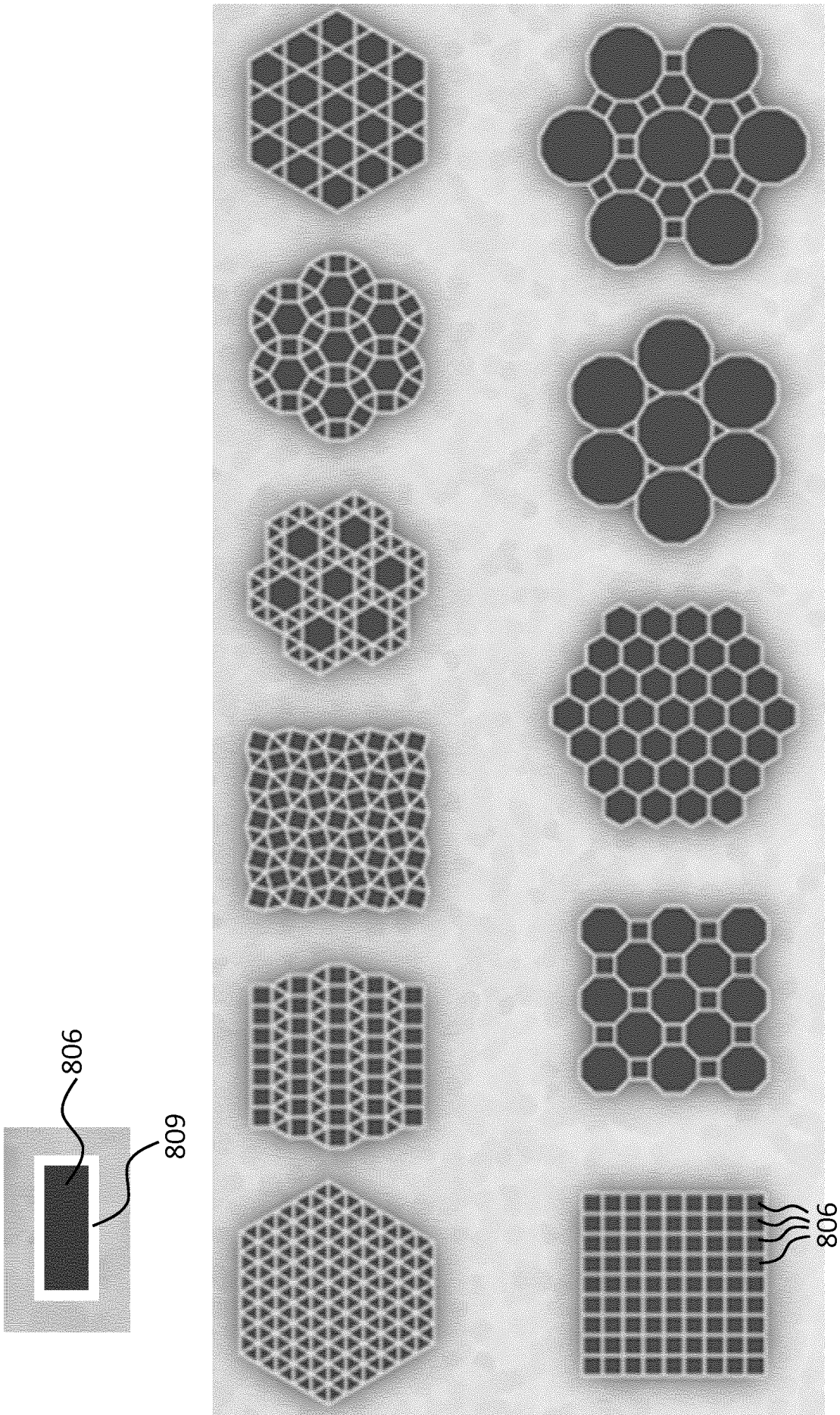


Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/064388

A. CLASSIFICATION OF SUBJECT MATTER

INV. G02B26/00 G02B26/02 G02B1/00 G02B5/28
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	US 2015/253564 A1 (SHINTO SUSUMU [JP] ET AL) 10 September 2015 (2015-09-10) paragraphs [0023], [0051], [0072]; claim 1; figures 1,3	1-15
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Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

12 February 2018

Date of mailing of the international search report

20/02/2018

Name and mailing address of the ISA/

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Pugno, Roberto

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/064388

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