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(71) Applicant: **OSTENDO TECHNOLOGIES, INC.** [US/US]; 6185 Paseo del Norte, Suite 200, Carlsbad, California 92011 (US).

(72) Inventors: **EL-GHOROURY, Hussein S.**; 6185 Paseo del Norte, Suite 200, Carlsbad, California 92011 (US). **PITCHUMANI, Mahesh**; 6185 Paseo del Norte, Suite 200, Carlsbad, California 92011 (US). **ALPASLAN, Zahir Y.**; 6185 Paseo del Norte, Suite 200, Carlsbad, California 92011 (US). **CHUANG, Chih-Li**; 6185 Paseo del Norte, Suite 200, Carlsbad, California 92011 (US). **MCNEILL, Dale A.**; 6185 Paseo del Norte, Suite 200, Carlsbad, California 92011 (US).

(74) Agents: **VINCENT, Lester J.** et al.; Blakely Sokoloff Taylor & Zafman LLP, 1279 Oakmead Parkway, Sunnyvale, California 94085 (US).

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# (54) Title: NON-TELECENTRIC EMISSIVE MICRO-PIXEL ARRAY LIGHT MODULATORS AND METHODS OF FABRICATION THEREOF

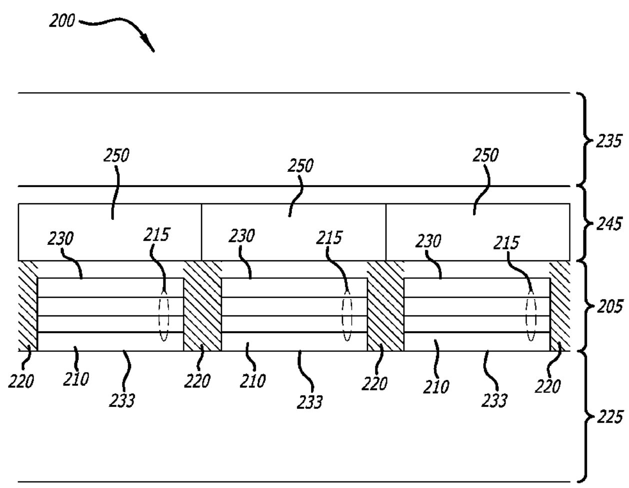


FIG. 2A

**(57) Abstract**: Emissive micro-pixel spatial light modulators with non-telecentric emission are introduced. The individual light emission from each multi-color micro-scale emissive pixel is directionally modulated in a unique direction to enable application-specific non-telecentric emission pattern from the micro-pixel array of the emissive spatial light modulator. Design methods for directionally modulating the light emission of the individual micro-pixels using micro-pixel level optics are described. Monolithic wafer level optics methods for fabricating the micro-pixel level optics are also described. An emissive multi-color micro-pixel spatial light modulator with non-telecentric emission is used to exemplify the methods and possible applications of the present invention: ultra-compact image projector, minimal cross-talk 3D light field display, multi-view 2D display, and directionally modulated waveguide optics for see-through near-eye displays.

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# NON-TELECENTRIC EMISSIVE MICRO-PIXEL ARRAY LIGHT MODULATORS AND METHODS OF FABRICATION THEREOF

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 62/271,637 filed December 28, 2015.

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

Non-telecentric emission spatial light modulators, emissive micro-pixel displays, ultra-compact image projectors, directional light modulators, multi-view 2D displays, 3D displays, near-eye displays, head-up displays.

### 2. Prior Art

Spatial light modulators (SLMs) are a class of optoelectronic devices having a planar array of micro-scale pixels that are typically used as an image source in display systems. Such light modulators typically fall in one of three distinctive categories: reflective, transmissive or emissive. Examples of reflective SLMs include micro mirror array devices and liquid crystal on silicon (LCoS) devices. Examples of transmissive SLMs include high temperature poly-silicon liquid crystal (HTPS) devices. Examples of emissive SLMs include emissive micro-pixel array devices. One example of an emissive micro-pixel array device may be based on the Quantum Photonic Imager or QPI® imager described in U.S. Patent Nos. 7,623,560, 7,767,479, 7,829,902, 8,049,231, 8,243,770 and 8,567,960 and organic light emitting diode (OLED) micro-pixel array devices. Both reflective and transmissive SLMs typically require an external light source to modulate images while an emissive SLM generates its own light. In general, all current categories of SLMs modulate telecentric light; meaning the modulated light bundles have their chief rays perpendicular to the plane of the light modulator pixel array. In the case of reflective and transmissive SLMs, telecentric light modulation is dictated by the design limitations of their external light source. Telecentric light emission is the only option available for emissive SLMs with a Lambertian emission profile such as OLED based SLMs.

Example micro-emissive solid state light-emitting display elements suitable for use with the embodiments herein include, without limitation, those described in U.S. Patent Nos. 7,623,560, 7,767,479, 7,829,902, 8,049,231, 8,243,770 and 8,567,960 . These SSL imagers feature high brightness, in a multi-color emissive micro-pixel spatial array with all of its needed drive circuitry in a single device. Within the context of this disclosure the term "SSL imager" is henceforth intended to mean an optoelectronics device that comprises an array of emissive micro-scale solid state light (SSL) emitting pixels. The SSL light emitting pixels of such an imager, hereinafter referred to as simply SSL imagers, are typically either a light emitting diode (LED) or laser diode (LD) whose on-off state is controlled by the drive circuitry contained within a CMOS device upon which the emissive micro-scale pixel array is formed or bonded. The pixels within the emissive micro-scale pixel array of an SSL imager are individually addressable through its drive circuitry, such as CMOS or the comparable, enabling an SSL imager to emit light that is modulated spatially, chromatically and temporally. The multiple colors emitted by an SSL imager share the same pixel optical aperture. In an SSL imager best suited for use with the embodiments herein, each SSL imager pixel emits at least partially collimated (or non-Lambertian) light, in the case of a QPI SSL imager, with an angle of divergence ranging, by design, from ±5° to ±45°. The size of the pixels comprising the emissive array of an SSL imager would typically be in the range of approximately 5-20 microns with the typical emissive surface area of the device being in the range of approximately 15-150 square millimeter. An SSL imager preferably can be designed with minimal gap between its emissive pixel array area and the device physical edge, allowing a multiplicity of SSL imagers, including QPI imagers, to be tiled to create any arbitrary size emissive display area.

Although all current categories of SLMs preferably modulate telecentric light, there is much to be gained from a non-telecentric light emission SLM. Since reflective and transmissive SLM's non-telecentric light modulation capability is limited by their external light source, and an emissive OLED-based SLM cannot achieve non-telecentric light emission by virtue of its Lambertian light emission profile, the SSL imager with its emissive multi-color micro-pixels that emits collimated (or non- Lambertian) light is uniquely qualified to achieve non-telecentric light modulation. It is therefore an objective of this invention to extend the design and manufacturing methods of an SSL imager to include the capability of non-telecentric light emission for the numerous possible applications that stand to benefit from such capability, some few of which are described herein by way of non-limiting examples only.

FIG. 1A illustrates the prior art design concept of a projection display that uses a telecentric light emission SLM. As illustrated in FIG. 1A, the divergence pattern of the light bundles 105 emitted from the telecentric emission SLM 110 dictates the use of a large diameter projection optics 115 which typically dictates the large optical track length 120, which in turn makes the overall design of a projection system that uses the telecentric emission SLM 110 overly bulky. It is therefore one of the objectives of this invention to introduce non-telecentric emission SLM methods that enable smaller diameter projection optics, and consequently achieve shorter optical track lengths and a substantially more compact overall projection system.

FIG. 1B illustrates the prior art designs of a 3D light field display that uses a telecentric light emission SLM, for example U.S. Patent Nos. 8,928,969, 8,854,724 and 9,195,053. In these types of displays, an array of lenses (130-132) are used whereby each of these lenses (130 for example) directionally modulates the light emitted from the sub-array of the SLM micro pixels 115 to subtend into a unique set of directions depending on the spatial position of each pixel within the sub-array of pixels. As illustrated in FIG. 1B, the divergence pattern of the telecentric light bundles 135 emitted from the pixels at the boundaries of each lens (130 for example) corresponding pixel sub-array would partially illuminate the adjacent lenses (131 and 132 for example). This effect, which is often referred to as “cross-talk”, causes undesirable “ghost” distortions in the directionally modulated 3D image. It is therefore another objective of this invention to introduce non-telecentric emission SLM methods that enable a 3D light field display exhibiting minimal cross-talk image distortion.

In the design of 3D displays, directional modulation of the emitted light is necessary to create the 3D viewing perception. In a typical 3D display, a backlight with uniform illumination in multiple illumination directions is required to display images of the same scene from different directions by utilizing some combination of spatial multiplexing and temporal multiplexing in the SLM. In these 3D displays, the light that typically comes from the directional backlight is usually processed by a directionally selective filter (such as diffractive plate or a holographic optical plate for example FIG. 1D, U.S. Patent No. 7,952,809) before it reaches the spatial light modulator pixels that modulate the light color and intensity while keeping its directionality.

Currently, prior art directional light modulators are a combination of an illumination unit comprising multiple light sources and a directional modulation unit that directs the light emitted by the light sources to a designated direction (see FIG. 1D, 1E & 1F). As illustrated in FIG. 1A, 1B & 1C which depict several variants of the prior art, an illumination unit is usually combined with an electro-mechanical movement device such as scanning mirrors, a rotating barriers (see U.S. Patent Nos. 6,151,167, 6,433,907, 6,795,221, 6,803,561, 6,924,476, 6,937,221, 7,061,450, 7,071,594, 7,190,329, 7,193,758, 7,209,271, 7,232,071, 7,482,730, 7,486,255, 7,580,007, 7,724,210, 7,791,810 and U.S. Patent Application Publication Nos. 2010/0026960 and 2010/0245957, or electro-optically such as liquid lenses or polarization switching (see U.S. Patent Nos. 5,986,811, 6,999,238, 7,106,519, 7,215,475, 7,369,321, 7,619,807, 7,952,809 and FIG. 1A, 1B & 1C).

In addition to being slow, bulky and optically lossy, the prior art directional backlight units typically need to have narrow spectral bandwidth, high collimation and individual controllability for being combined with a directionally selective filter for 3D display purposes. Achieving narrow spectral bandwidth and high collimation requires device level innovations and optical light conditioning, increasing the cost and the volumetric aspects of the overall display system. Achieving individual controllability requires additional circuitry and multiple light sources, increasing the system complexity, bulk and cost. It is therefore an objective of this invention to introduce directional light modulators that overcome the limitation of the prior art, thus making it feasible to create distortion free 3D and multi-view 2D displays that provide the volumetric advantages plus a viewing experience over a wide viewing angle.

Additional objectives and advantages of this invention will become apparent from the following detailed description of preferred embodiments thereof that proceeds with reference to the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

The invention is illustrated by way of example, and not by way of limitation, in the Figs. of the accompanying drawings in which like reference numerals refer to similar elements.

FIG. 1A illustrates prior art light projection that uses a telecentric spatial light modulator.

FIG. 1B illustrates a prior art directional light modulator that uses a telecentric spatial light modulator.

FIG. 1C illustrates a prior art directional light modulator that uses a liquid lens.

FIG. 1D illustrates a prior art directional light modulator that uses scanning mirrors.

FIG. 1E illustrates a prior art directionally modulated backlight.

FIG. 1F illustrates a prior art directional display using a directionally modulated backlight.

FIG. 2A illustrates a cross sectional view of a generalized non-telecentric emissive micro pixel light modulator (SSL imager) in accordance with this invention.

FIGS. 2B-1 AND 2B-2 illustrate top views of the light coupling topside of the photonic layer of the non-telecentric emissive micro pixel light modulator of this invention.

FIGS. 2C-1 AND 2C-2 illustrate the directional light modulation aspects of the non-telecentric emissive micro pixel directional light modulator of this invention.

FIGS. 2D-1, 2D-2 AND 2D-3 illustrate the geometrical aspects of the directional light modulation pixel groups of the non-telecentric emissive micro pixel directional light modulator of this invention.

FIG. 3A illustrates a schematic cross section of an embodiment of this invention in which the array pixel level micro optical elements are realized as de-centered refractive optical elements (ROE).

FIG. 3B illustrates a face view of the directional modulation layer of an embodiment of this invention in which the array pixel level micro optical elements are realized as de-centered refractive optical elements (ROE).

FIG. 4A illustrates a schematic cross section of an embodiment of this invention in which the array pixel level micro optical elements are realized as tilted refractive optical elements (ROE).

FIG. 4B illustrates a face view of the directional modulation layer of an embodiment of this invention in which the array pixel level micro optical elements are realized as tilted refractive optical elements (ROE).

FIG. 5A illustrates a schematic cross section of a waveguide exit of an embodiment of this invention in which the array pixel level micro optical elements are realized as spatially modulated refractive optical elements (ROE).

FIG. 5B illustrates a top view of the waveguide exit of an embodiment of the invention in which the array pixel level micro optical elements are realized as spatially modulated refractive optical elements (ROE).

FIG. 6A illustrates an embodiment of this invention in which the array pixel level micro optical elements are realized as diffractive optical elements (DOE).

FIG. 6B illustrates an example in which the SSL imager pixels' diffractive optical elements are realized using multiple dielectric layers that form a blazed grating.

FIG. 6C illustrates an example of the case when multi-level gratings are used to realize the desired diffraction angle across the multiple wavelengths light emission bandwidth of the SSL imager pixels.

FIG. 7A illustrates a wafer level optics (WLO) fabrication process of the pixel level micro optical elements of the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 7B illustrates a lithographic mask set used in the wafer level optics (WLO) fabrication process of the pixel level micro optical elements of the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 7C illustrates a wafer level optics (WLO) fabrication process of a de-centered pixel level micro optical elements of the non-telecentric emissive micro pixel light modulator of this invention.

FIGS. 7D-7M illustrate a wafer level optics (WLO) fabrication process sequence of the pixel level micro optical elements of the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 8A illustrates a design method of an ultra compact display projector enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 8B illustrates the superior optical efficiency and uniformity of the ultra compact display projector of FIG. 8A enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 8C illustrates the superior volumetric efficiency of the ultra compact display projector of FIG. 8A enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 9 illustrates a design method of a minimum cross-talk light field modulator enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 10A illustrates a top view of a multi-view 2D display enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 10B illustrates a side view of a multi-view 2D display enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 11A illustrates a side view of a waveguide light modulator enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 11B illustrates a top view of a waveguide light modulator enabled by the non-telecentric emissive micro pixel light modulator of this invention.

FIG. 11C illustrates a side view of a tapered waveguide light modulator enabled by the non-telecentric emissive micro pixel light modulator of this invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

References in the following detailed description of the present invention to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearances of the phrase “in one embodiment” in various places in this detailed description are not necessarily all referring to the same embodiment.

In the description to follow, references are made to the word groups, such as in a directional modulation groups of micro pixels and similar references. When a non-telecentric emissive micro-pixel array light modulator in accordance with the present invention is to display a light field, reference to a group of pixels or to the corresponding micro optical elements is a reference to the pixels or micro optical elements associated with a single hogel. When the present invention is to display one or more two dimensional scenes at the same time, reference to a group of pixels or to the corresponding micro optical elements is a reference to all pixels of the non-telecentric emissive micro-pixel array light modulator or to one of the groups of pixels associated with a respective two dimensional scene.

The embodiments herein combine the emissive micro pixel array capabilities of an SSL imager with a monolithically fabricated pixel level micro optical element (referred to in the claims as a directional modulation layer) to create a non-telecentric spatial light modulator that performs the combined functionalities of color and brightness as well as directional modulation of the light emitted from each of its emissive micro pixels. Pixel level micro optical elements are a class of wafer level optics (WLO) which, in accordance with the present invention, are fabricated monolithically on an SSL imager wafer from semiconductor dielectric materials, such silicon oxide or silicon nitride, or alternatively with a UV curable polymer using ultra violet (UV) imprint lithography. As used herein, wafer level or wafer means a device or matrix of devices having a diameter of at least 2 inches, and more preferably 4 inches or more. Among the primary advantages of WLO are the ability to fabricate small feature micro-scale optical elements and the ability to precisely align multiple layers of WLO optical elements with the optoelectronics elements of devices such as the SSL imager or a CMOS sensor, for example. The alignment precision that can be achieved by typical WLO fabrication techniques can be much less than one micron. The combination of the individual pixel addressability of the emissive micro pixel array of the SSL imager and a precisely aligned micro pixel level optical elements, herein referred to collectively as the “non-telecentric SSL imager”, creates the first non-telecentric emissive SLM which enables the numerous applications highlighted in the previous discussion and detailed henceforth.

In the embodiments herein, pixels’ color, brightness and directional light modulation is achieved by the combination of the SSL imager emissive pixels and light bending achieved by their associated micro pixel level optics that collectively comprise the non-telecentric emission SSL imager.

FIG. 2A illustrates a general cross sectional view of an exemplary non-telecentric emissive micro pixel (spatial) light modulator (SSL imager) 200 that may be used with the invention. As illustrated in FIG. 2A, the overall structure of the exemplary SSL imager 200 is a stack of multiple layers comprising the photonic micro pixels array layer 205 with the control layer 225 bonded to its non-emissive backside 233 and the directional modulation layer 245 and the cover glass layer 235 (optional in some embodiments) bonded to its emissive topside 230. The photonic layer 205 comprises the array of emissive multi-color micro pixels 210 with each micro pixel being a photonic cavity defined by its reflective sidewalls 220 and its reflective top and back side contacts that form the topside 230 and backside 233 of the photonic layer 205; respectively. The photonic layer 205 is a stack of multiple color emission III/V semiconductor sub-layers 215 which, when pixelated (i.e., formed into a micro pixel array using semiconductor lithography, etch and deposition techniques), form a multi-color stack of heterojunction diodes within the photonic cavity of each of the micro pixels 210 comprising the micro pixel array 200. Each of the micro pixels 210 is electrically coupled to the control layer 225 with multiple contact metal micro vias through the backside 233 and sidewalls 220 to control the on-off state of each pixel color emission sub-layer 215. The control layer 225 is a complementary metal oxide semiconductor (CMOS) comprising multiple digital logic sub-layers designed to convert (or process) the SSL imager digital input, coupled through the CMOS contact vias, into electrical signals that are coupled to each pixel to modulate their emitted light color and brightness. Depending on the geometry of the CMOS technology process used to fabricate the control layer 225, for example 180-nm CMOS versus 65-nm or smaller geometry CMOS, the control layer 225 can be used to implement either merely the micro pixel driving circuitry or to further implement the complex digital image processing of the digital image input that would lead to generating the micro pixel's electrical drive signal.

FIGS. 2B-1 and 2B-2 illustrate top views of the light coupling top side 230 of the photonic layer 205 of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 according to embodiments herein. As illustrated in FIGS. 2B-1 and 2B-2, the light coupling topside 230 of each micro pixel 210 is comprised of a multiplicity of waveguides 260, which are formed on the topside sub-layer 230 using semiconductor lithography, etch and deposition techniques. As shown in FIGS. 2B-1 and 2B-2, the waveguides 260 may be located at various positions with respect to the light coupling top side 230 of the photonic layer 205. Depending on the waveguides 260 diameter, depth spacing pattern, and the dielectric semiconductor material used, the angle of divergence of the collimated light emission from micro pixels 210 can be tailored within an angle of divergence ranging from ±5° to ±45°. Referring back to FIG. 2A, the at least partially collimated light emitted from each of the micro pixels 210 is coupled onto their corresponding micro pixel level optical elements 250 comprising the directional modulation layer 245.

FIGS. 2C-1 and 2C-2 illustrates the functional aspects of the directional modulation layer 245 of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein. As illustrated in the multiple panels of FIGS. 2C-1 and 2C-2, the micro optical element 250 associated with each of the micro pixels 210 may be designed to direct (or directionally modulate) the light coupled onto it from its corresponding micro pixels 210 to a unique direction relative to its perpendicular axis. The multiple panels of FIGS. 2C-1 and 2C-2 illustrate two possible examples of the directional modulation patterns that can be realized by the directional modulation layer 245 of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein. The first panel of FIG. 2C-1 illustrates an example in which the directional modulation layer 245 is designed to realize a convergent directional modulation pattern with the light emitted from the directional modulation group 270 of micro pixels 210 directionally converge systematically toward the perpendicular axis from the peripheral edges of the directional modulation group 270 toward its center. The second panel of FIG. 2C-2 illustrates an example in which the directional modulation layer 245 is designed to realize a divergent directional modulation pattern with the light emitted from the directional modulation group 270 of micro pixels 210 directionally diverge systematically away from the perpendicular axis from the center of the directional modulation group 270 toward its peripheral edges. In FIGS. 2C-1 and 2C-2, the arrows placed at the center of each of the micro pixels 210 are meant to indicate the direction of the chief ray of the light bundle emitted from each of the micro pixels 210 as represented by the angle of each respective arrow in the $(x, y)$ plane and the length of each respective arrow representing or suggestive of its angle from the perpendicular axis.

FIGS. 2D-1, 2D-2 and 2D-3 illustrate the geometrical aspects of the directional modulation pixel groups 270 of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein. As illustrated in the multiple panels of FIGS. 2D-1, 2D-2 and 2D-3, the geometrical shape of the directional modulation pixel groups 270, in terms of the number of pixels representing its dimensions in the $(x, y)$ plane of the micro pixel array, can possibly be a square (see FIG. 2D-1), rectangle (see FIG. 2D-3) or hexagonal (see FIG. 2D-2) among many possible shapes depending on the intended application. The size, in micro pixels, of the directional pixel group 270 can extend to include either a sub-region of the SSL imager micro pixel array or the entire micro pixel array of the SSL imager. In the case when the directional pixel group 270 extends over a sub-region of the SSL imager micro pixel array, it could be a repeated directional modulation pattern or in some cases it could be a unique directional modulation pattern for each directional modulation pixel group 270 depending on the application.

The pixel level micro optical elements 250 of the directional modulation layer 245 would have the same planar dimensions in the $(x, y)$ plane as their respective emissive micro pixel 210. The pixel level micro optical elements 250 could be realized as either a refractive optical element (ROE) or a diffractive optical element (DOE). In either of these cases, the optical design parameters of each of the pixel level micro optical elements 250 would be selected to realize the selected directional modulation pattern across the modulation pixel group 270 as explained earlier. The pixel level micro optical elements 250 would be fabricated monolithically on the SSL imager wafer from either semiconductor dielectric materials, such silicon oxide or silicon nitride, or from polymer using ultra violet (UV) imprint lithography. In one embodiment, the fabrication of the pixel level micro optical elements 250 would be accomplished as a sequence of lithography, etch and deposition steps directly on the topside (the light emissive side) of the SSL imager wafer that already incorporates on its topside the photonic layer 205, which incorporates the array of micro pixels 230, and on its backside the CMOS control layer 225. In another embodiment of this invention, the fabrication of the pixel level micro optical elements 250 would be accomplished as a sequence of lithography, etch and deposition steps on one side of a wafer size cover glass layer 235, then the micro optical elements 250 side of the cover glass wafer is aligned and bonded directly on the top side (the light emissive side) of the SSL imager wafer that already incorporates the photonic layer 205 and the CMOS control layer 225. In yet another embodiment of this invention, the fabrication of the pixel level micro optical elements 250 would be accomplished as a sequence of lithography, etch and deposition steps on one side of the cover glass layer 235, then the micro optical elements 250 side of the glass cover wafer is used as a substrate to which the multiple sub-layers constituting the photonic layer 205, upon which the array of micro pixels 230 are formed, and the CMOS control layer 225 would be bonded sequentially to fabricate the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein.

In another embodiment, the fabrication of the pixel level micro optical elements 250 would be accomplished using WLO techniques in which the micro optical elements 250 would be formed by embossing a UV curable polycarbonate polymer on one side of the cover glass layer 235, then the formed micro optical elements 250 side of the wafer is aligned and bonded directly on the top side (the light emissive side) of the SSL imager wafer that already incorporates the photonic layer 205 and the CMOS control layer 225. In this method, the layer of pixel level micro optical elements 250 would be fabricated using a master mold of the array of micro optical elements 250 that is first fabricated using micro machining or laser ablation techniques, then copied on a UV transparent mold that would be used to emboss the UV curable polycarbonate polymer on one side of a wafer-size cover glass 235. The embossing of the array of micro optical elements 250 would also incorporate the embossing of alignment marks that would be used to align the micro optical elements 250 to their respective micro pixels 230 during the bonding process with the SSL imager wafer that already incorporates the photonic layer 205 and the CMOS control layer 225. In this case, the bonding of the glass cover wafer 235 with the embossed micro optical elements 250 to the of the SSL imager wafer, that already incorporates the photonic layer 205 and the CMOS control layer 225, would be accomplished using UV curable optical glue that would be spread or sprayed on the bonding surface of either or both wafers, then the wafers are brought into alignment using alignment marks previously incorporated onto the surface of each wafer, then the aligned wafer pair is scanned with a UV laser beam or illuminated by a UV flood light to cure the optical glue bonding layer placed on the bonding surfaces of the two wafers.

*"De-centered" Refractive Micro Optical Element (ROE)* – FIG. 3A illustrates one instantiation of the embodiment of this invention in which the array pixel level

micro optical elements 250 are realized as refractive optical elements (ROE). In this embodiment the pixel level refractive micro optical elements 250 directional modulation aspects are realized using de-centered micro lenses 250-1 formed by successive layers of dielectric materials 310 and 320 with different indexes of refraction. FIG. 3A and 3B are side and top views; respectively, of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein when realized as de-centered refractive micro optical elements 250-1. In this embodiment, the array of pixel level micro optical elements 250-1 would be fabricated monolithically at the wafer level as multiple layers of semiconductor dielectric materials, such silicon oxide for the low index layer 310 and silicon nitride for the high index layer 320, using semiconductor lithography, etch and deposition techniques. As illustrated in FIG. 3A, the array pixel level micro optical elements 250-1 are realized using multiple layers, the dielectric materials 310 and 320 with different indexes of refraction successively (sequentially) deposited to form the refractive surfaces of the pixel level micro optical elements 250-1. The top view panel of FIG. 3B illustrates the de-centered micro lenses method when used to realize an exemplary directional modulation group 270 whereby the de-centeration in the $(x, y)$ plane of the refractive micro optical elements 250-1 would be proportional to the directional modulation to be realized by each of the refractive micro optical elements 250-1. As illustrated in FIG. 3B, in order to realize the desired directional modulation pattern across the intended directional modulation pixel group 270, the center of the refractive micro optical elements 250-1 associated with the micro pixel 230 at the center of the directional modulation group 270 would be aligned with the center of its respective pixel 230 but the center of the refractive micro optical elements 250-1 away from the center of directional modulation pixel group 270 would have their centers offset from the center of their respective pixels 230 with such an offset gradually increasing for micro optical elements 250-1 further away from the center of the directional modulation pixel group 270. The de-centeration offset of the refractive micro optical elements 250-1 would converge toward or diverge away from the center of the directional modulation pixel group 270 when the directional modulation pattern converges toward or diverges away from the center of the directional modulation pixel group 270, respectively. The angular separation $\delta\theta$ between the directional modulation realized by the individual de-centeration of the refractive micro optical elements 250-1 would be made proportional to the desired directional modulation of the angular extent $\Theta$. For example, for an NxN pixels modulation group 270 having the angular extent $\Theta$, the angular separation δθ between the directional modulation realized by the individual de-centeration of the refractive micro optical elements 250-1 would be equal to $\Theta/N$.

*"Tilted" Refractive Micro Optical Element (ROE)* – FIG. 4A illustrates yet another instantiation of the embodiment of this invention in which the array of pixel level micro optical elements 250 are realized as refractive optical elements (ROE). In this embodiment, the pixel level refractive micro optical elements 250 directional modulation aspects are realized using tilted micro lenses 250-2 formed by successive layers of dielectric materials 410 and 420 with different indexes of refraction. FIG. 4A and 4B are side and top views; respectively, of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein when realized using tilted refractive micro optical elements 250-2. In this embodiment, the array of pixel level micro optical elements 250-2 would be fabricated monolithically at the wafer level as multiple layers of semiconductor dielectric materials, such as silicon oxide for the low index layer 410 and silicon nitride for the high index layer 420, using semiconductor lithography, etch and deposition techniques. As illustrated in FIG. 4A the array pixel level micro optical elements 250-2 are realized using multiple layers dielectric materials 410 and 420 with different indexes of refraction successively (sequentially) deposited to form the refractive surfaces of the pixel level micro optical elements 250-2. The top view panel of FIG. 4A illustrates the tilted micro lenses method when used to realize an exemplary directional modulation group 270 whereby the tilting of optical axis of the refractive micro optical elements 250-2 would be proportional to the directional modulation to be realized by each of the refractive micro optical elements 250-2. As illustrated in FIG. 4A, in order to realize the desired directional modulation pattern across the intended directional modulation pixel group 270, the optical axis of the refractive micro optical elements 250-2 associated with the micro pixel 230 at the center of the directional modulation group 270 would be aligned with the axis perpendicular to the $(x, y)$ plane of the refractive micro optical

elements 250-2 but the optical axis of the refractive micro optical elements 250-2 away from the center of directional modulation pixel group 270 would have their optical axis inclined from the axis perpendicular to the $(x, y)$ plane with such an inclination gradually increasing for micro optical elements 250-2 further away from the center of the directional modulation pixel group 270. The tilting of the optical axis of the refractive micro optical elements 250-1 would converge toward or diverge away from the axis perpendicular to the $(x, y)$ plane when the directional modulation pattern converges toward or diverges away from the center of the directional modulation pixel group 270, respectively. The angular separation $\delta\theta$ between the directional modulation realized by the individual optical axis tilting of the refractive micro optical elements 250-2 would be made proportional to the desired directional modulation of the angular extent $\Theta$. For example, for an NxN pixels modulation group 270 having the angular extent $\Theta$, the angular separation $\delta\theta$ between the directional modulation realized by the individual de-centeration of the refractive micro optical elements 250-2 would be equal to $\Theta/N$.

*Spatially Modulated Refractive Micro Optical Element (ROE)* – FIG. 5A illustrates yet another embodiment of this invention in which the array of pixel level micro optical elements 250 are realized as refractive optical elements (ROE). In this embodiment, the pixel level refractive micro optical elements 250 directional modulation aspects are realized using spatially modulated micro lenses 250-3 formed by successive layers of dielectric materials 510 and 520 with different indexes of refraction. FIG. 5A and 5B are side view and top view illustrations; respectively, of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein when realized using the spatially modulated refractive micro optical elements 250-3. As illustrated in FIG. 5A and FIG. 5B, in this embodiment the centers of the pixel level refractive micro optical elements 250-3 are aligned with their respective emissive micro pixels 205 and their optical axes are also aligned perpendicular to the $(x, y)$ plane but in the case of this embodiment, the directional modulation is realized by using Fourier (or field) lens micro optical elements 250-3 combined with an emissive micro pixel 205 having a single waveguide 260 that is spatially modulated, or appropriately positioned in the $(x, y)$ plane, within the pixel's optical aperture. In Fig. 5B, the single waveguide is illustrated by the solid circle at the center of the pixel illustrated, with the limits of its possible spatial modulation in the x and y directions being illustrated by the dashed circles 265. In this embodiment, the Fourier lens' aspects of the micro optical elements 250-3 may cause its chief ray to be either aligned with, or inclined from, the perpendicular to the $(x, y)$ plane when the single waveguide 260 of its respective emissive micro pixel 205 is positioned at the center or offset from its optical aperture; respectively, with the inclination of chief ray of the micro optical elements 250-3 from the perpendicular to the $(x, y)$ plane being in the direction of the axis extended from the center of waveguide 260 to the center of the pixel's micro optical element 250-3 and with angular inclination that is proportional to the spatial offset of single waveguide 260 from the center of its respective emissive micro pixel 205. FIG. 5B illustrates the micro pixel's single waveguide spatial offset method of this embodiment when used to realize an example directional modulation group 270 whereby the micro pixel's 230 single waveguide 260 spatial offset from the center of its optical aperture in the $(x, y)$ plane would be proportional to the directional modulation to be realized by each of the refractive micro optical elements 250-3. As illustrated in FIG. 5A, in order to realize the desired directional modulation pattern across the intended directional modulation pixel group 270, the micro optical elements 250-3 at the center of the directional modulation group 270 would have the single waveguide 260 of its associated emissive micro pixel 205 aligned with the center of its optical aperture but the micro optical elements 250-3 away from the center of directional modulation pixel group 270 would have their associated emissive micro pixels 205 having their single waveguide 260 spatial offset from the centers of their optical apertures gradually increasing for the emissive micro pixel 205 and micro optical element 250-3 pairs further away from the center of the directional modulation pixel group 270. The spatial offset of single waveguide 260 of the emissive pixels 230 and their respective refractive micro optical elements 250-3 would converge toward or diverge away from the center of the emissive micro pixels 205 of the directional modulation pixel group 270 when the directional modulation pattern diverges away from or converges toward the center of the directional modulation pixel group 270, respectively. The angular separation $\delta\theta$ between the directional modulation realized by the individual single waveguide 260 spatial offset associated with the refractive micro optical elements 250-3 would be made proportional to the desired directional modulation the angular extent $\Theta$. For example, for an NxN pixels modulation group 270 having the angular extent $\Theta$, the angular separation δθ between the directional modulation realized the refractive micro optical elements 250-3 single waveguide 260 spatial offset would be equal to $\Theta/N$.

In other applications, the spatially modulated refractive micro optical element (ROE) of the directional modulation layer described above need not have the micro optical element 250-3 at the center of the directional modulation group or have the single waveguide 260 of its associated emissive micro pixel 205 aligned with the center of its optical aperture. Further, the directional modulation layer 245 of the embodiment of Figs. 5A and 5B might be geometrically, but not physically, intentionally shifted in an x,y plane relative to the emissive micro pixels 205. The result would be that all the micro optical elements 250-3 so shifted would have less truncation on one end and a greater truncation on the other end. This would create a directional bias in the emission which would then be controllable by the intentional positioning of each single waveguide in the group, or pixel array, creating the bias while preserving the range of directional modulation available by selective positioning of the single waveguides.

*"Diffractive" Micro Optical Element (DOE)* – FIG. 6A illustrates an embodiment of this invention in which the array pixel level micro optical elements 250 are realized as diffractive optical elements (DOE). In this embodiment the pixel level micro optical elements 250 directional modulation aspects are realized using micro grating 250-4 formed by successive layers of either metal rails or dielectric materials with different indexes of refraction. FIG. 6A and 6B are side view and top view illustrations; respectively, of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein when realized using micro grating diffractive optical elements 250-4. In this embodiment the array of pixel level micro grating elements 250-4 would be fabricated monolithically at the wafer level as multiple layers of semiconductor dielectric materials, such silicon oxide for the low index layer 610 and silicon nitride for the high index layer 620, or metal rails using semiconductor lithography, etch and deposition techniques. As illustrated in FIG. 6A the array pixel level micro grating elements 250-4 are realized using

multiple layers of dielectric material with different indexes of refraction successively (sequentially) deposited to form the diffractive surfaces of the pixel level micro optical elements 250-4 (Fig. 6B). The top view of FIG. 6A illustrates the micro DOE method when used to realize an exemplary directional modulation group 270 whereby the micro grating optical element 250-4 diffraction angle (measured from the normal axis) and axial orientation of the micro grating diffractive optical elements 250-4 in the $(x, y)$ plane would be proportional to the directional modulation to be realized by each of the diffractive micro optical elements 250-4.

As illustrated in FIG. 6A, a convergent (or divergent depending on the selected design parameters of the diffractive optical elements 250-4) directional modulation pattern would be realized across the intended directional modulation pixel group 270 by having the axial orientation of the diffractive micro optical elements 250-4 associated with each of the emissive micro pixels 205 be aligned with radial axis of the directional modulation group 270 and having their diffraction angle be proportional to their radial distance from the center of the modulation group 270. The angular separation $\delta\theta$ between the directional modulation realized by the individual diffractive micro optical elements 250-4 would be proportional to the desired directional modulation angular extent or field of view (FOV) $\Theta$ of the directional modulation pixel group 270. For example in the case of the illustration of FIG. 6A that shows a modulation group 270 comprised of 8x8 of the micro pixels 205, when the directional modulation angular extent or field of view (FOV) $\Theta$ equals 45 degrees, the angular separation $\delta\theta$ between the directional modulation realized by the individual diffractive micro optical elements 250-4 would be 5.625 degrees.

The SSL imager 200 pixels' diffractive optical elements 250-4 can be realized using transmission grating such as blazed grating or rail grating, for example. The illustration of FIG. 6B shows an example in which the SSL imager 200 pixels' diffractive micro optical elements 250-4 are realized using multiple dielectric layers 610 and 620 having different indexes that form a blazed grating, for example using high index silicon nitride for layer 610 and lower index silicon oxide for layer 620. In the illustration of FIG. 6B the slant angle and pitch of the blazed grating would be selected to realize the desired diffraction angle of each diffractive micro optical elements 250-4 and consequently the directional modulation of their associated emissive micro pixels 205 of the SSL imager 200. In the example of FIG. 6B, the index of the layer 610 would preferably be selected to match the index of the pixel's photonic layer 215, thus for example, using the higher index silicon nitride for layer 610. The index difference between the high index layer 610 and the low index layer 620 of the pixels' diffractive micro optical elements 250-4 would govern the maximum diffraction angle of the pixels' diffractive optical elements 250-4 and consequently the index difference between the two dielectric layers 610 and 620 would be a design parameter that would affect the total angular extent or field of view (FOV) realizable by the directional modulation groups 270 of the SSL imager 200 of this embodiment. For example although FIG. 6A shows a lower index dielectric material 620 capping the high index layer 610, it would be possible to have the high index layer 610 be the top layer of the SSL imager 200 pixels in order to maximize the pixel's diffraction angular extent and consequently the realizable field of view (FOV) of the SSL imager 200 directional modulation groups 270. In order to maximize the index difference between the two layers 610 and 620 of the pixels' diffractive micro optical elements 250-4, it would be beneficial in this case for the top layer 620 to be an air gap. In this case, the cover glass layer 235 would be bonded on top side of the SSL imager 200 with the addition of spacers that would allow a thin air gap layer 620 between the high index layer 610 and the glass cover 235. In order to further maximize the field of view (FOV) realizable by the SSL imager 200 directional modulation groups 270 of this embodiment, it would also be possible to etch the diffractive micro optical elements' 250-4 lower layer 610 surface directly into the top side 230 of the photonic layer 215 of the SSL imager 200 pixels since, as explained earlier, the photonic layer 215 is fabricated from III/V semiconductor material, such as gallium nitride (GaN) for example, which typically has high index of refraction. Similar to the previous case of this embodiment, in this case it would also be beneficial to maximize the realizable FOV even further by having the top layer 620 of the diffractive micro optical elements 250-4 be an air gap layer. In this case also, the cover glass layer 235 would be bonded on top side of the SSL imager 200 with the addition of spacers that would allow a thin air gap layer between the high index layer 610 and the glass cover 235.

As explained earlier, the SSL imager 200 pixels can emit light with multiple wavelengths from each pixel aperture. In the case when the SSL imager 200 pixels emit light with multiple wavelengths, the diffractive optical elements 250-2 would be realized using wideband transmission gratings or multi-level gratings designed to achieve the desired diffraction angle across the light emission bandwidth of the SSL imager 200 pixels. In the case when wideband transmission gratings are used, the SSL imager 200 pixels diffractive optical elements 250-2 could be realized using a multiplicity of layers of dielectric materials with alternating high and low indexes for each such layer index. The index of such layers together with the formed grating slant angle and pitch would be selected to realize the desired pixel's diffractive angle within each sub-band of the SSL imager 200 pixels' light emission bandwidth. FIG. 6C illustrates an example of the case when multi-level gratings are used to realize the desired diffraction angle across the multiple wavelengths light emission bandwidth of the SSL imager 200 pixels. In this example case, two dielectric layers 630 and 640 with differing indexes are used to form a multi-level grating with a different grating pitch within each layer whereby the grating pitch of each layer being designed to dominantly diffract light within a given sub-band of the SSL imager 200 pixels light emission bandwidth. The pitch and index of each of the two layers 630 and 640 would be selected through an iterative design process that would take into account the collective diffractive action of the grating multi-level across the entire multiple wavelength emission bandwidth of the SSL imager 200 pixels. In the example of FIG. 6C, the index of the layer 630 would preferably be selected to match the index of the pixel's photonic layer 205. In addition, it would be possible to have the high index layer 630 be the top layer of the SSL imager 200 pixels in order to maximize the pixel's diffraction angular extent and consequently the realizable field of view (FOV) of the SSL imager 200 directional modulation groups 270. In this embodiment, the cover glass layer 235 would be bonded on top side of the SSL imager 200 with the addition of spacers that would allow a thin air gap layer between the high index layer 630 and the glass cover 235.

*Directional Modulation Layer 245 Fabrication Method* – As explained earlier, the pixel level micro optical elements 250 of the previous embodiments would be used to directionally modulate, collect and/or collimate the light emitted from their corresponding emissive micro pixels 205 and as such would have optical apertures which are equal to and precisely aligned, within at least less than 10% accuracy, with their corresponding micro pixels 230 of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of this invention. The pixel level micro optical elements 250 of the previous embodiments can be fabricated using a variety of nano-imprint lithographic techniques such as patterning using Phase, Grayscale, entire domain or sub domain masks, additive lithographic sculpting that use binary masks as well as various direct write techniques. Photo resist (heat) reflow and molding could also be employed for fabrication of the micro optical elements 250 to increase the smoothness of the formed surfaces. Additive Lithography using a sub domain binary mask set will be used herein as an example to illustrate a typical method for the fabrication of exemplary ROE pixel level micro optical elements 250 of the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of this invention.

*Wafer Level Optics Mask Set* – The fabrication process sequence of the pixel level micro optical elements 250 begins with the fabrication of a set of lithography sub domain masks that captures the binary shape specifications of the micro optical elements 250. The fabrication process of the sub domain masks involves identifying the symmetry within the specified features of the pixel level micro optical elements 250 to be fabricated and breaking down the identified symmetry to an orthogonal or non orthogonal set of basis. FIG. 7A illustrates the orthogonal and non orthogonal basis set for an exemplary rotationally symmetric pixel level refractive micro optical elements 250 generated by this process. The specified binary surface shape of the micro optical elements 250 will be achieved later during the fabrication process by controlling the exposure dose of each element of the orthogonal or non orthogonal basis set during lithography as illustrated in FIG. 7B.

As illustrated in FIG. 7A, the rotationally symmetric refractive micro optical elements 250 would be represented by the two dimensional basis set of orthogonal (rings) or non orthogonal (circles) elements. For realizing the pixel level micro optical elements 250 as a de-centered ROC of the previous embodiment, at each micro pixel 230 position, the required de-centering shift is applied to the generated basis set and then truncated accordingly after each of the basis is aligned with the micro pixel 230 aperture specified by the design. FIG. 7C illustrates two example cases, one where the micro optical elements 250 axis lies at the center of the aperture of the micro pixel 230 and a second case where the micro optical elements 250 axis is shifted from the center of the aperture of the micro pixel 230. This process is then repeated across the entire array of micro pixels 230 mask alignment reference coordinates to create a multilayer mask set for the full aperture of the emissive micro pixel light modulator (SSL imager) 200 device. Equivalent orthogonal and non-orthogonal basis elements are then aligned with the array of emissive micro pixel 230 mask alignment reference coordinates across the SSL imager 200 aperture to form separate mask layers. These mask layers can then be separated and placed on well known locations on a single reticle or on multiple reticles to be used in the wafer level micro optics lithography fabrication process of the micro optical elements 250. This entire process of masking layers formation can be accomplished using a standard mask editing software such as LEdit typically used in the creation of semiconductors lithography masks. It should be noted that this mask formation process would be repeated for every optical surface comprising the pixel level micro optical elements 250 to create a full mask set for the wafer level optic fabrication of the non-telecentric emissive micro pixel light modulator (SSL imager) 200.

Although the preceding discussion outlined the process of forming the lithography mask set for the case when the pixel level micro optical elements 250 are realized in accordance with the embodiment described earlier as a de-centered ROE, a person skilled in the art will readily know how to apply the described lithography mask set formation process in the cases of other described embodiments when the micro optical elements 250 are realized as tilted ROE or as a DOE.

*Wafer Level Optics Fabrication Sequence* – FIGS. 7D-7M illustrate the fabrication process sequence of the pixel level micro optical elements 250. After the wafer level optics mask set is formed in accordance with the preceding discussion, a substrate of choice is coated with a thin layer, preferably few microns, of a dielectric material, herein referred to as dielectric-1 (FIG. 7D), using semiconductor material deposition tools such as plasma enhanced chemical vapor deposition (PECVD). The deposited dielectric-1 layer could be amorphous but needs to be sufficiently transparent within the target optical spectrum, for example within the visible light 400nm to 650nm spectrum and specifically selected to introduce minimal stresses on the substrate wafer. The deposited dielectric-1 layer would typically be the low index material surrounding other high index material layers that would comprise the pixel level micro optical elements 250. Alignment marks are then patterned onto the topside of the deposited dielectric-1 layer to be used for aligning subsequent layers of the pixel level micro optical elements 250.

A photoresist appropriately chosen and characterized is then coated on top of dielectric-1 layer and Additive Lithography is performed using the fabricated mask set to create a negative of that surface of the pixel level micro optical elements 250 (FIG. 7E). In the Additive Lithography process, the negative surface would be created on the photoresist layer by the successive alignment and exposure using the various masks of the set with an alignment tolerance of less than 100nm or preferably in the range of 50nm (FIG. 7F). The created shape of the photoresist surface would be optimized by adjusting the exposure and focus offset parameters for each of the lithographical steps for the various masks of the set as illustrated in FIG. 7B. This step is followed by the appropriate metrology measurements to confirm that the created photoresist negative surface is compliant with the surface design specification (or optical prescription) of the 1$^{st}$ surface of the pixel level micro optical elements 250.

Once the specification compliance of the photoresist negative surface is confirmed, the micro optical elements 250 would be etched using the appropriate chemistry on  a reactive ion etching (RIE) tool that can provide 1:1 selectivity between the photoresist and the dielectric-1 layers (FIG. 7G). Etching time needs to be adjusted based on pre-characterized etch rate in order to avoid over-etching into the dielectric-1 layer and to ensure that the shape on the photoresist is faithfully transferred on the dielectric-1 layer with minimal defects formed during the etching step. A metrology measure following this step is used to confirm the dielectric-1 layer etched surface is compliant with the surface design specification (or optical prescription) of the micro optical elements 250. After the etch and metrology steps, the wafer dielectric-1 layer surface is thoroughly cleaned to ensure removal of all polymer residues and other contaminants from the fabricated surface of the wafer. At the end of this step, the first surface of the micro optical elements 250 would be created on the dielectric-1 layer in accurate alignment with the micro pixels 230 across the entire wafer surface with the created optical surface.

After the dielectric-1 layer surface is fabricated, the wafer is coated with a relatively thick conformal layer of a high index dielectric-2 layer (FIG. 7H). The thickness of dielectric-2 layer should be sufficient to accommodate the optical features of the micro optical elements 250 while being highly transparent with minimal stress. The deposited surface of the dielectric-2 layer then undergoes a planarization process using chemical mechanical polishing (CMP) tool to obtain a nearly flat surface across the wafer with minimal total thickness variation (TTV) (FIG. 7I). The dielectric-2 layer wafer surface is then coated with photoresist then processed, in similar steps as described for dielectric-1 layer, using Additive Lithography followed by etching to create the 2$^{nd}$ surface of the pixel level micro optical elements 250 on the dielectric-2 layer surface (FIG. 7J-L).

After the fabrication of the 1$^{st}$ and 2$^{nd}$ surfaces of the pixel level micro optical elements 250 as shown in Figs. 7K and 7L, a third layer of dielectric material, designated as dielectric-3 layer, is deposited on the top of the wafer surface and planarized to the required thickness and TTV specifications (FIG. 7M). The dielectric constant and index of refraction of the dielectric layers dielectric-1, dielectric-2 and dielectric-3 would be selected based on the optical prescription of the pixel level micro optical elements 250 and typically in most applications dielectric-1 and dielectric-3 would have the same index of refraction value that lower than dielectric-2 index of refraction value.

The described WLO fabrication steps would be repeated on the top of dielectric-3 layer wafer surface if a second optical element is to be added in accordance with the optical prescription of the pixel level micro optical elements 250.

After all the optical elements of the pixel level micro optical elements 250 are fabricated on top of the substrate wafer, the wafer surface is coated with a bonding intermediary layer, polished to the appropriate bonding specification then aligned bonded, using the alignment marks added earlier in the process, to the top photonic layer 205 surface.

In one embodiment of this invention, the WLO fabrication process described in the preceding paragraphs is used to fabricate the pixel level micro optical elements 250 on the top of the cover glass wafer 235 as a substrate then the fabricated wafer is used as a substrate upon which the pixelated photonic layers stack 205 would be bonded and formed sequentially. At the end of that fabrication sequence, the formed wafer would be aligned bonded to the topside of the CMOS control layer 225.

In another embodiment of this invention, the WLO fabrication process described in the preceding paragraphs is used to fabricate the pixel level micro optical elements 250 on top of the cover glass wafer 235 as a substrate then the fabricated wafer is aligned bonded to the photonic layer 205 top surface of the wafer formed separately that comprises the photonic layer stack 205 bonded sequentially to the topside of the CMOS control layer 225.

In yet another embodiment of this invention, the WLO fabrication process described in the preceding paragraphs is used to fabricate the pixel level micro optical elements 250 on top of the wafer formed separately that comprises the photonic layer stack 205 bonded sequentially to the topside of the CMOS control layer 225, then the cover glass wafer is bonded on the top of the fabricated pixel level micro optical elements 250. In the WLO fabrication process for this case, the 2$^{nd}$ surface of the pixel level micro optical elements 250 will be fabricated first on top of the pixelated photonic layers stack 205, then the 1$^{st}$ surface of the pixel level micro optical elements 250 would be fabricated on top. In still other embodiments, particularly using other fabrication processes described herein for the directional modulation layers and using this fabrication process, the glass cover layer 235 would be bonded on the top side of the SSL imager 200 with the addition of spacers that would allow a thin air gap layer 620 between the high index layer 610 and the glass cover 235. Each of the aforementioned embodiments would have its advantages depending on the intended application.

FIGS. 7D-7M illustrate the WLO fabrication process described in the preceding paragraphs to fabricate the pixel level micro optical elements 250 on the on top of the cover glass wafer 235 as a substrate. Although FIGS. 7D-7M illustrate the described the WLO fabrication process in the case of the pixel level micro optical elements 250 being a ROE fabricated on top the glass cover wafer 235 as a substrate, the described fabrication sequence equally applies in the case of the numerous embodiments described including the case when the pixel level micro optical elements 250 being a DOE fabricated within the context of any of the WLO fabrication process embodiments of the previous paragraphs.

*Ultra Compact Projector* – FIG. 8A illustrates a design method of an ultra compact display projector enabled by the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein. In this embodiment, the directional modulation layer 245 of the SSL imager 200 is designed to realize a convergent directional modulation pattern causing the light emitted from the directional modulation group 270 of micro pixels 210 to directionally converge systematically toward the perpendicular axis from the peripheral edges of the directional modulation group 270 toward its center. In this case, the directional modulation group 270 extends across the entire emissive optical aperture of the SSL imager 200. As illustrated in FIG. 8A, the pixel level micro optical elements 250 would directionally modulate the light emitted from SSL imager 200 micro pixels to achieve maximum fill factor of the optical aperture of the first optical element L-1 of the projection optics 810 which in turn is designed to further redirect the light rays toward the second optical element L-2 optical aperture while maintaining the fill factor at a maximum. Optical elements L3 and L4 are used for magnification of the projected image. The projector design of this embodiment achieves less than an 8mm optical track length with a 3.6x6.4 mm SSL imager emissive aperture size while achieving a fairly uniform optical efficiency. The actual projector has cross-sectional dimensions of 5.82mm x 8.05mm, with a height of 7.86mm. Besides its volumetric efficiency, the ultra compact display projector of FIG. 8A would enable the attainment of high optical efficiency and brightness uniformity. As shown in FIG. 8B, the projector design of this embodiment achieves almost 83% optical efficiency with less than 15% center to corner roll off compared to 22.8% optical efficiency for a design that does not use the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of the embodiments herein. With the minimal optical track length it achieves, the projector design of this embodiment was used to fabricate the ultra compact, full color projector pictured in FIG. 8C having a total volume of less than 0.3cc. To the best of the inventors' knowledge, this is volumetrically the smallest HD projector ever designed and fabricated, which makes it ideal for mobile display applications such as embedded and attached mobile projectors as well as near-eye head mounted displays (HMD).

*Minimum Cross-Talk Light Field Modulator* – FIG. 9 illustrates a design method of a minimum cross-talk light field modulator enabled by the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of this invention. In this embodiment the "cross-talk" between holographic elements (hogels) and the undesirable 3D image "ghost" distortions it causes would be substantially reduced or eliminated altogether by making the SSL imager 200 emission non-telecentric across the optical apertures of each of the hogel lenses 930-932 as illustrated in FIG. 9. That is to say in this embodiment, the directional modulation layer 245 of the SSL imager 200 would be designed to realize a convergent directional modulation pattern causing the light emitted from the directional modulation group 270 of micro pixels 210 to directionally converge systematically toward the perpendicular axis from the peripheral edges of the directional modulation group 270 toward its center. In the case of this embodiment, the directional modulation group 270 would extend across the sub-array of SSL imager 200 emissive micro pixels corresponding to (or associated with) the optical aperture of each of the hogel lenses 930-932 of FIG. 9. With the design method of this embodiment the pixel level micro optical elements 250 of the SSL imager 200 sub-array of micro pixels 210 associated with each of the hogel lenses 930-932 would be designed such that the light emission from the sub-array of micro pixels 210 would remain substantially confined within the optical apertures of their associated hogel lenses 930-932 apertures, thus minimizing the light leakage or cross-talk between adjacent the hogel lenses 930-932. With that being achieved, the light leakage between light field views modulated by the SSL imager 200 would be minimized, making the views from different directions having no ghost interference from other directions.

In this embodiment, the light emitted from each of the SSL imager 200 micro pixels 210 would be sufficiently collimated and directionally modulated (or directed) by the pixel's micro optical elements 250 to efficiently fill in their associated hogel lens with minimal or substantially no light leakage into adjacent hogel lenses. Thus in addition to minimizing the cross-talk between directionally modulated views, the directional light modulator of FIG. 9 enabled by the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of this invention would also achieve higher optical efficiency and uniformity across its field of view (FOV).

*Multi-View Display* – FIG. 10A and FIG. 10B illustrate a top view and side view, respectively, of a multi-view 2D display design method enabled by the non-telecentric emissive micro pixel light modulator (SSL imager) 200 of this invention. In this embodiment, the SSL imager 200 emissive pixels 210 array and their associated micro optical elements 250 of the directional modulation layer 245 would be spatially partitioned into directional modulation sub-arrays or directional modulation groups 270. As illustrated in FIG. 10B the directional modulation layer 245 of the SSL imager 200 of this embodiment may be designed to realize a divergent directional modulation pattern that would cause the light emitted from the directional modulation group 270 of micro pixels 210 to directionally diverge systematically into a unique set of directions away from the perpendicular axis of the directional modulation group 270. In this embodiment, the size of the directional modulation group 270 in terms of the number of emissive pixels 210 will determine the number of views that can supported by the multi-view display. For example, a 64-view multi-view display can be realized using an 8x8 directional modulation group 270 of FIG. 10A with each of the pixels in each of the modulation groups across the display aperture being designed to emit light in a unique direction that is uniformly and angularly spaced within the targeted field of view (FOV) of the multi-view display. In this embodiment, the light emitted from each of the SSL imager 200 micro pixels 210 would be sufficiently collimated and directionally modulated to a specific unique direction by the pixel's micro optical elements 250.

*Waveguide Light Modulator* – FIG. 11A illustrates a design method of a *Waveguide Light Modulator* enabled by the non-telecentric emissive micro pixel light modulator of this invention. As illustrated in FIG. 11A, the *Waveguide Light*

*Modulator* of this embodiment would be comprised of the SSL imager 200 with its directional modulation layer coupled onto the optical input aperture 1120 of the waveguide 1110 which has the reflective optics layer 1130 coated to one of its sides to define its optical output aperture 1140. In this embodiment the SSL imager 200 emissive pixels 210 array and their associated micro optical elements 250 of the directional modulation layer 245 would direct the light emitted from each of the SSL imager 200 pixels in a unique direction within the waveguide angular range of the waveguide 1110. In the case of a total internal reflection (TIR) waveguide 1110, such as that illustrated in the FIG. 11A, the light emitted from each of the SSL imager 200 pixels would be directionally modulated by the pixel's associated micro optical elements 250 in a unique direction within the tangential (lateral) and vectorial (elevation) planes that will set forth the wave guiding angle of the light emitted from that pixel as well as the lateral divergence from the pixel's $(x, y)$ coordinates. The directional modulation of the light emitted by the SSL imager 200 pixels in lateral plane would serve to determine the total expansion (or magnification) of the image being modulated by the SSL imager 200 pixel array as the light emitted from its pixel array propagate through the waveguide. In effect the directional modulation of the light emitted by the SSL imager 200 pixels in lateral plane would serve to determine the x-axis magnification factor of the image being modulated by the SSL imager 200 pixel array and coupled into the waveguide. The directional modulation of the light emitted by the SSL imager 200 pixels in vectorial plane would serve to determine the angle at which the light emitted (and modulated) from each of the SSL imager 200 pixels would propagate through the waveguide. With the waveguide reflective optics layer 1130 typically being designed to break the TIR condition for light rays being guided through the waveguide at progressively lower angle further away from the waveguide input optical aperture 1120 into which the SSL imager 200 is optically coupled, the light emitted by the SSL imager 200 pixels and directionally modulated by its micro optical elements 250 in vectorial plane at a progressively smaller angles within the waveguide TIR angular range would propagate further away from waveguide input optical aperture 1120 before its TIR guiding condition is broken (collapsed) by the waveguide reflective optics layer 1130 directing the light more directly toward the output aperture 1140 of the waveguide 1110. In effect the directional modulation of the light emitted by the SSL imager 200 pixels in vectorial plane would serve to determine the y-axis magnification factor of the image being modulated by the SSL imager 200 pixel array and coupled into the waveguide. When the directional modulation of the light emitted by the SSL imager 200 pixels in the tangential (lateral) and vectorial planes are properly selected for each of its pixels, the directional modulation of the light emitted by the SSL imager 200 of this invention would enable the magnification and relay of the image it is modulating and coupling into the waveguide input optical aperture 1120 to the waveguide output optical aperture 1140. As an alternative, the output aperture may itself include transmissive optics to break the TIR condition at the output aperture 1140.

The directional modulation design method of this embodiment is further illustrated in FIG. 11B which shows a top view of the SSL imager 200 enabled *Waveguide Light Modulator* of this invention. In FIG. 11B the SSL imager 200 pixels' coordinates within the waveguide input optical aperture 1120 are designated as $(x, y)$ coordinates while the *Waveguide Light Modulator* pixels' coordinates within the waveguide output optical aperture 1140 are designated as $(X, Y)$ coordinates. As illustrated in FIG. 11B, the SSL imager 200 pixels directional modulation angles in the lateral and vectorial planes cause the light emitted from each of the SSL imager 200 pixels and coupled into the waveguide at a given $(x, y)$ coordinates within the waveguide input optical aperture 1120 to be uniquely mapped to given $(X, Y)$ coordinates within the waveguide output optical aperture 1140. In effect the SSL imager 200 pixels' directional modulation method of this embodiment together with an appropriately designed waveguide reflective optics layer 1130 would enable the synthesis of a given optical transfer function that realizes both magnification and relay between the waveguide input and output optical apertures 1120 and 1140; respectively. It should be added that in this embodiment, the collimation angle of the light bundles emitted by the SSL imager 200 pixels would be selected to be outside the TIR angular range of the waveguide 1110 for proper functioning of the output aperture 1140 without special provisions for the emission.

*Tapered Waveguide Light Modulator* – In an alternative embodiment, illustrated in FIG. 11C, the SSL imager 200 based *Waveguide Light Modulator* may be realized using the tapered waveguide 1150 whereby the tapering angle (or slope) of one surface of the waveguide 1150 is selected to break the TIR condition for light rays being guided through the waveguide 1150 at a progressively lower angle (closer to a line perpendicular to the local waveguide surface) further away from the waveguide input optical aperture 1160 into which the SSL imager 200 is optically coupled. The tapering of one surface of the waveguide 1150 in this embodiment performs the equivalent optical function of the diffractive optics layer 1130 of the previous embodiment. In this embodiment, the SSL imager 200 emissive pixels 210 array and their associated micro optical elements 250 of the directional modulation layer 245 would direct the light emitted from each of the SSL imager 200 pixels in a unique direction within the waveguide angular range of the tapered waveguide 1150. As illustrated in the FIG. 11C, the light emitted from each of the SSL imager 200 pixels would be directionally modulated by the pixel's associated micro optical elements 250 in a unique direction within the tangential (lateral) and vectorial (elevation) planes that will set forth the wave guiding angle of the light emitted from that pixel as well as the lateral divergence from the pixel's $(x, y)$ coordinates. The directional modulation of the light emitted by the SSL imager 200 pixels in the lateral plane would serve to determine the total expansion of the image being modulated by the SSL imager 200 pixel array as the light emitted from its pixel array propagates through the tapered waveguide 1150. In effect, the directional modulation of the light emitted by the SSL imager 200 pixels in lateral plane would serve to determine the x-axis magnification factor of the image being modulated by the SSL imager 200 pixel array and coupled into the waveguide. The directional modulation of the light emitted by the SSL imager 200 pixels in vectorial plane would serve to determine the angle at which the light emitted (and modulated) from each of the SSL imager 200 pixels would propagate through the waveguide. With the tapered surfaces of the waveguide 1150 being designed to break the TIR condition for light rays being guided through the waveguide at progressively lower angle (closer to a perpendicular to the local surface of the tapered waive guide 1150) further away from the waveguide input optical aperture 1160 into which the SSL imager 200 is optically coupled, the light emitted by the SSL imager 200 pixels and directionally modulated by its micro optical elements 250 in the vectorial plane at a progressively lower angles within the waveguide TIR angular range would propagate further away from waveguide input optical aperture 1160 before it's TIR guiding condition is broken (collapsed) by the tapered surface of the waveguide 1160. In effect, the directional modulation of the light emitted by the SSL imager 200 pixels in the vectorial plane would serve to determine the y-axis magnification factor of the image being modulated by the SSL imager 200 pixel array and coupled into the tapered waveguide 1160. When the directional modulation of the light emitted by the SSL imager 200 pixels in the tangential (lateral) and vectorial planes are properly selected for each of its pixels, the directional modulation of the light emitted by the SSL imager 200 of the embodiments herein would enable the magnification and relay of the image it is modulating and coupling into the tapered waveguide 1160 input optical aperture 1120 to the waveguide output optical aperture 1140. In effect the SSL imager 200 pixels directional modulation method of this embodiment together with an appropriately designed tapered waveguide 1150 would enable the synthesis of a given optical transfer function that realizes both magnification and relay between the tapered waveguide 1150 input and output optical apertures 1160 and 1170; respectively. It should be added that in this embodiment, the collimation angle of the light bundles emitted the SSL imager 200 pixels would be selected to be within the TIR angular range of the tapered waveguide 1150. As an alternate, certain surfaces of the tapered waveguide such as part of the lower surface of the tapered waveguide may be coated with a reflective coating, if desired, to allow a last reflection when the TIR condition has already been broken.

It should be noted that the two previous embodiments of the SSL imager 200 based *Waveguide Light Modulator* can be used to create optical see-through (OST) near-eye or head-mounted display (HMD). In each of these embodiments, as alternate embodiments, the SSL imager may instead have its output coupled into an input aperture at the end or edge of the waveguide 1110 and achieve the same of similar results. Also the waveguides themselves may have other shapes, and are not limited to rectangular shapes as shown.

Thus, using the wafer level fabrication techniques for the wafer level optics, the entire non-telecentric emissive micro-pixel array light modulator may be fabricated at the wafer level and then the wafer level assembly diced to obtain the final products.

Also, while Fig. 2C-1 illustrates an embodiment wherein the light converges from the center of the pixel group or the entire array, and Fig. 2C-2 illustrates an embodiment wherein the light diverges from the center of the pixel group or the entire array, neither are a limitation of the invention, as in some applications, light from all pixels in a group or the entire array may be directed in the same general direction, though normally in different angles to present the full image or images for viewing in an undistorted form. This may require a counter distortion at the directional modulator layer to achieve the undistorted image for viewing. Further, the directional modulation layer may include two or more distinct pixel groups, one for presenting a first image at one location or depth, and one or more other images at one or more additional location or locations or depths.

In the foregoing description and in the claims, reference is made to a directional modulation layer. It is to be understood that the word layer is used in a general sense to identify the layer or multiple layers that determine the spatial modulation of the non-telecentric emissive micro-pixel array light modulator. Also it should be understood that while certain fabrication techniques for the directional modulation layer have been described herein, each with respect to a respective embodiment, such techniques are also applicable to use in other embodiments using the same form of directional modulation layer and/or fabrication sequence. Thus by way of example, the use of UV curable polycarbonate polymer or the embossing to form a specific embodiment is exemplary, and such techniques and the sequence of operations for forming the resulting ROE are exemplary only, and the use of UV curable polycarbonate polymer or embossing may be used to form any ROE based directional modulation layer and to fabricate the non-telecentric emissive micro-pixel array light modulator of the present invention in any sequence of fabrication operations. Further, unless the context dictates otherwise, references to a pixel group or pixel groups includes a reference to a group that encompasses the entire SSL imager emitter area

Thus those skilled in the art will readily appreciate that various modifications and changes can be applied to the embodiments of the invention without departing from its scope defined in and by the appended claims. It should be appreciated that the foregoing examples of the invention are illustrative only, and that the invention can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The disclosed embodiments, therefore, should not be considered to be restrictive in any sense. The scope of the invention is indicated by the appended claims, rather than the preceding description, and all variations which fall within the meaning and range of equivalents thereof are intended to be embraced therein.

## CLAIMS

What is claimed is:

1. A non-telecentric emissive micro-pixel array light modulator comprising:

a control layer;

pixelated, multiple color emission III/V semiconductor layers stacked above the control layer and controllable from the control layer to emit at least partially collimated, pixelated light that is modulated chromatically and temporally; and

a directional modulation layer of optical elements above the pixelated multiple color emission III/V semiconductor layers, each optical element to directionally modulate light coupled onto it from a corresponding pixel to a respective direction relative to an axis perpendicular to the pixelated, multiple color emission III/V semiconductor layers.

2. The non-telecentric emissive micro-pixel array light modulator of claim 1 further comprising a cover glass layer over the directional modulation layer.

3. The non-telecentric emissive micro-pixel array light modulator of claim 2 wherein the cover glass layer is spaced apart from the directional modulation layer to provide an air gap between the directional modulation layer and the cover glass layer.

4. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer comprises refractive micro optical elements.

5. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer comprises diffractive micro optical elements.

6. The non-telecentric emissive micro-pixel array light modulator of claim 5 wherein the diffractive micro optical elements comprise blazed gratings or rail gratings.

7. The non-telecentric emissive micro-pixel array light modulator of claim 6 wherein the directional modulation of the directional modulation layer is determined by the slant angle and pitch of the blazed grating.

8. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer comprises semiconductor dielectric materials.

9. The non-telecentric emissive micro-pixel array light modulator of claim 8 wherein the directional modulation layer comprises multiple dielectric layers of silicon oxide or silicon nitride.

10. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer comprises a UV curable polymer.

11. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the pixelated, multiple color emission III/V semiconductor layers are divided into groups, each comprising a plurality of pixels.

12. The non-telecentric emissive micro-pixel array light modulator of claim 11 wherein each group of pixels is organized into a square, rectangle or hexagonal pattern.

13. The non-telecentric emissive micro-pixel array light modulator of claim 11 wherein the directional modulation layer comprises patterns, each directional modulation layer pattern corresponding to a respective pixel pattern, each directional modulation layer having the same directional modulation pattern.

14. The non-telecentric emissive micro-pixel array light modulator of claim 11 wherein the directional modulation layer comprises patterns, each directional modulation layer pattern corresponding to a respective pixel pattern, each directional modulation layer having a unique directional modulation pattern.

15. The non-telecentric emissive micro-pixel array light modulator of claim 11 wherein each directional modulation layer pattern directionally modulates light coupled onto it to a respective converging pattern.

16. The non-telecentric emissive micro-pixel array light modulator of claim 11 wherein each directional modulation layer pattern directionally modulates light coupled onto it to a respective diverging pattern.

17. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer comprises diffractive micro optical elements, and wherein the diffractive directional modulation layer comprises successive layers of either metal rails or dielectric material with different indexes of refraction.

18. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer directionally modulates light coupled onto it to a respective diverging pattern.

19. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer directionally modulates light coupled onto it to a respective converging pattern.

20. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer is comprised of pixel level refractive micro optical elements in the form of de-centered micro lenses of successive layers of dielectric materials with different indexes of refraction.

21. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer is comprised of pixel level refractive micro optical elements in the form of tilted micro lenses of successive layers of dielectric materials with different indexes of refraction.

22. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein:

the pixilated light emitted by the pixelated, multiple color emission III/V semiconductor layers is at least partially collimated by a waveguide for each pixel emitting the light from each of the stacked layers of the pixelated, multiple color emission III/V semiconductor layers;

each optical element of the directional modulation layer is a Fourier lens;

centers of each optical element of the directional modulation layer are aligned with a respective pixel of the pixelated, multiple color emission III/V semiconductor layers; and

the position of the waveguides, each with respect to a respective optical element, is spatially modulated to provide a desired directional modulation pattern.

23. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer is a diffractive directional modulation layer comprised of micro gratings formed by successive layers of either metal rails or dielectric materials with different indexes of refraction.

24. The non-telecentric emissive micro-pixel array light modulator of claim 23 wherein the micro gratings are wideband transmission gratings or multilevel gratings.

25. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer is a diffractive directional modulation layer comprised of micro gratings formed by multiple layers of silicon oxide and silicon nitride.

26. The non-telecentric emissive micro-pixel array light modulator of claim 1 wherein the directional modulation layer directionally modulates light coupled onto it from a corresponding pixel to a respective converging direction, and further comprising projection optics positioned to receive converging light from the non-

telecentric emissive micro-pixel array light modulator and project the converging light, thereby forming a multicolor projector.

27. The non-telecentric emissive micro-pixel array light modulator of claim 1, together with a waveguide, the non-telecentric emissive micro-pixel array light modulator being coupled to an input aperture of the waveguide, the waveguide also having an output aperture, the non-telecentric emissive micro-pixel array light modulator being positioned on the waveguide and the directional modulation layer being selected to direct an image from the pixelated multiple color emission III/V semiconductor layers into the input aperture, to be reflected by total internal reflection before exiting the waveguide through the output aperture of the waveguide.

28. The non-telecentric emissive micro-pixel array light modulator of claim 1, together with a tapered waveguide, the non-telecentric emissive micro-pixel array light modulator being coupled to an input aperture of the tapered waveguide in a region of the tapered waveguide of a first thickness, the tapered waveguide also having an output aperture in a region of the tapered waveguide of a second thickness, the second thickness being less than the first thickness, the non-telecentric emissive micro-pixel array light modulator being positioned on the tapered waveguide and the directional modulation layer being selected to direct an image from the pixelated multiple color emission III/V semiconductor layers to be reflected by at least a first internal surface of the tapered waveguide by total internal reflection before exiting the tapered waveguide through the output aperture of the tapered waveguide as a result of the breaking of the total internal reflection caused by the taper of the tapered waveguide.

29. A method of making anon-telecentric emissive micro-pixel array light modulator having a control layer, pixelated, multiple color emission III/V semiconductor layers stacked above the control layer and controllable from the control layer to emit at least partially collimated, pixelated light that is modulated chromatically and temporally, a directional modulation layer of optical elements above the pixelated multiple color emission III/V semiconductor layers, each optical

element to directionally modulate light coupled onto it from a corresponding pixel to a respective direction relative to an axis perpendicular to the pixelated, multiple color emission III/V semiconductor layers, and a cover glass layer over the directional modulation layer comprising:

fabricating the directional modulation layer on the cover glass layer using the cover glass layer as a substrate;

bonding the pixelated, multiple color emission III/V semiconductor layer stack to the directional modulation layer on the cover glass layer; and,

bonding the pixelated, multiple color emission III/V semiconductor layer stack to a CMOS control layer; or

fabricating the directional modulation layer on the cover glass layer using the cover glass layer as a substrate; and

bonding the directional modulation layer to the pixelated, multiple color emission III/V semiconductor layer stack as already bonded to the CMOS control layer, or

bonding the pixelated, multiple color emission III/V semiconductor layer stack to a CMOS control layer;

fabricating the directional modulation layer on the pixelated, multiple color emission III/V semiconductor layer stack; and

bonding the cover glass layer to the directional modulation layer.

30. A method of fabricating an ultra compact display projector comprising:

providing a control layer;

providing a pixelated, multiple color emission III/V semiconductor layers stacked above the control layer and controllable from the control layer to emit at least partially collimated, pixelated light across an emissive optical aperture that is modulated chromatically and temporally;

providing a directional modulation layer of optical elements above the pixelated multiple color emission III/V semiconductor layers and extending across the entire emissive optical aperture, each optical element to directionally modulate light coupled onto it from a corresponding pixel to a respective converging direction relative to an axis perpendicular to the directional modulation layer;

providing projection optics, including a first optical element for receiving the converging light from the directional modulation layer, a second optical element for receiving light from the first optical element, and one or more additional optical elements for receiving light from the second optical element to magnify a projected image, the optical elements directionally modulating the light emitted to achieve maximum fill factor of the optical aperture of the first optical element, the first optical element redirecting the light rays toward an optical aperture the second optical element while maintaining the fill factor at a maximum, the second optical element redirecting the light to the one or more additional optical elements for receiving light from the second optical element to magnify the projected image.

31. A method of fabricating a minimum cross-talk light field modulator comprising:

providing a control layer;

providing a pixelated, multiple color emission III/V semiconductor layers stacked above the control layer and controllable from the control layer to emit at least partially collimated, pixelated light that is modulated chromatically and temporally;

providing a directional modulation layer of optical elements above the pixelated multiple color emission III/V semiconductor layers, the optical elements being organized in groups, each group of optical elements representing a hogel of the light field, each optical element within a group of optical elements to directionally modulate light coupled onto it from a corresponding pixel to a respective converging direction toward a center of the respective group of optical elements relative to an axis perpendicular to the directional modulation layer, causing the pixelated light emitted from the respective group of optical elements to directionally converge systematically toward the axis perpendicular to the directional modulation layer such that the light from the optical elements remains substantially confined within optical apertures of associated hogel lens apertures, thus minimizing the light leakage or cross-talk between adjacent the hogel lenses.

32. A method for guiding an image comprising of a plurality of pixel outputs in a total internal reflection waveguide comprising the steps of:

directionally modulating a plurality of imager pixel outputs using a plurality of respective micro optical elements wherein the micro optical elements are configured to directionally modulate the respective imager pixel outputs in a total internal reflection waveguide in a unique direction within a tangential or lateral, and a vectorial or elevation plane, to define a waveguiding angle of the imager pixel outputs and a lateral divergence from a respective pixel's $(x, y)$ coordinates; whereby the tangential or lateral plane determines a total expansion or magnification of an image being modulated as the imager pixel outputs propagate through the waveguide.

33. The method of claim 32 wherein the directional modulation of the imager pixel outputs in the tangential or lateral plane defines an x-axis magnification factor of an image being modulated and the directional modulation of the imager pixel outputs in a vectorial or elevation plane defines an angle at which the imager pixel outputs propagate through the waveguide.

34. A method for minimizing optical cross-talk in a light field display comprising the steps of:

directionally modulating a plurality of light field imager pixel outputs in a sub array of micro pixels associated with a hogel lens using a plurality of respective micro optical elements; whereby the respective micro optical elements confine the respective light field imager pixel outputs within the optical aperture of the hogel lens.

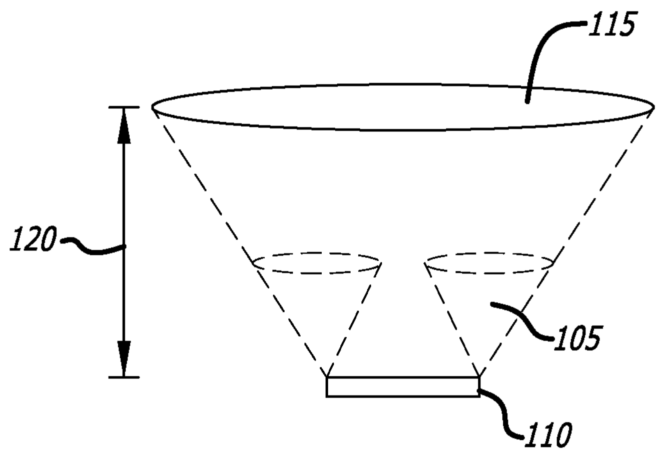



FIG. 1A
(Prior Art)

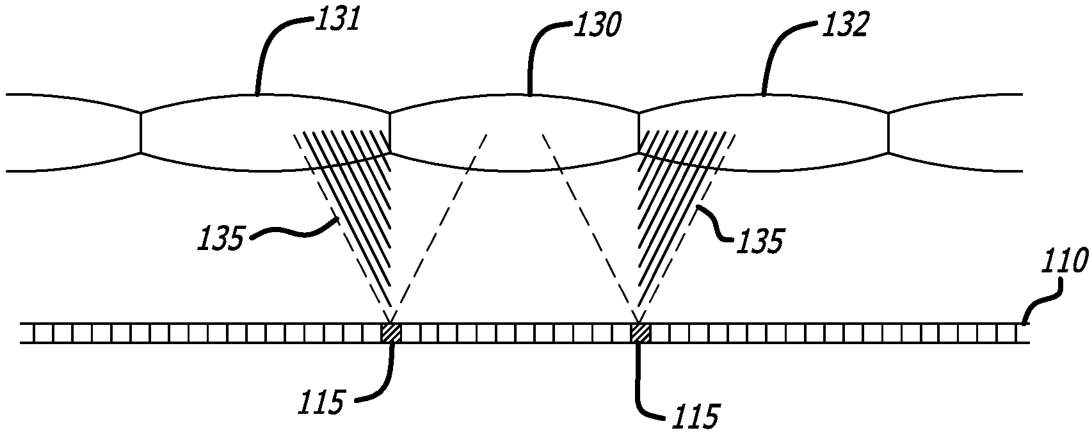



FIG. 1B
(Prior Art)

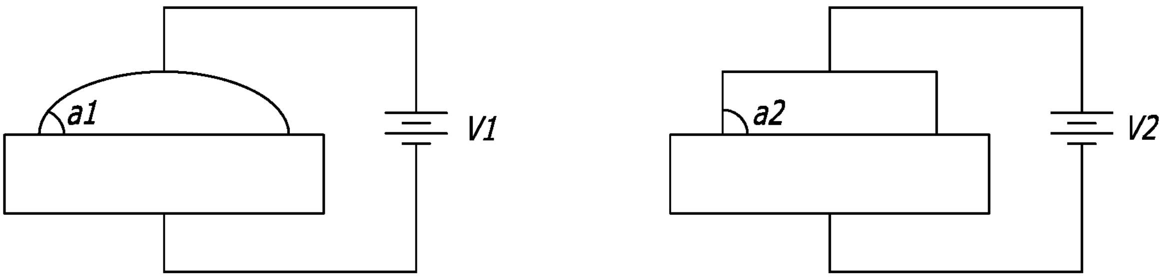



FIG. 1C
(Prior Art)

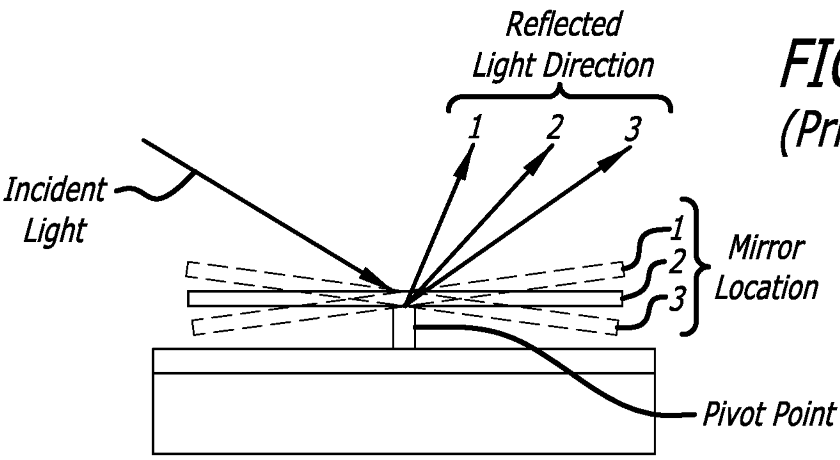
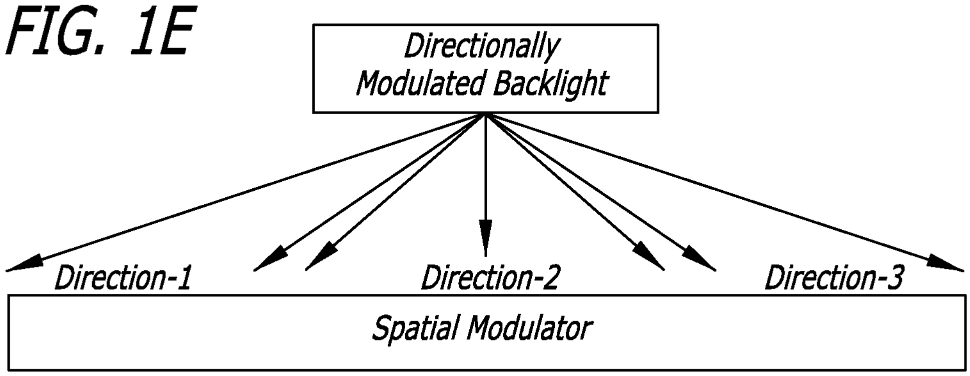



FIG. 1D
(Prior Art)

FIG. 1E


Directionally Modulated Backlight
Direction-1
Direction-2
Direction-3
Spatial Modulator

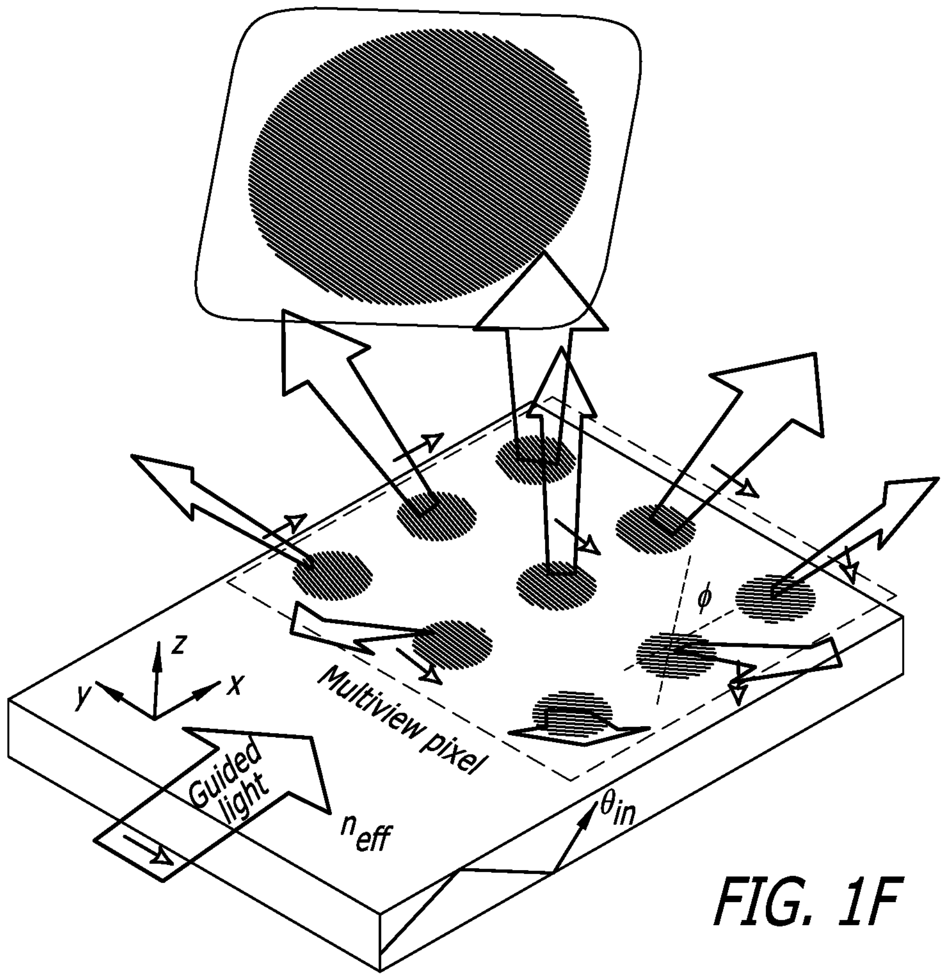
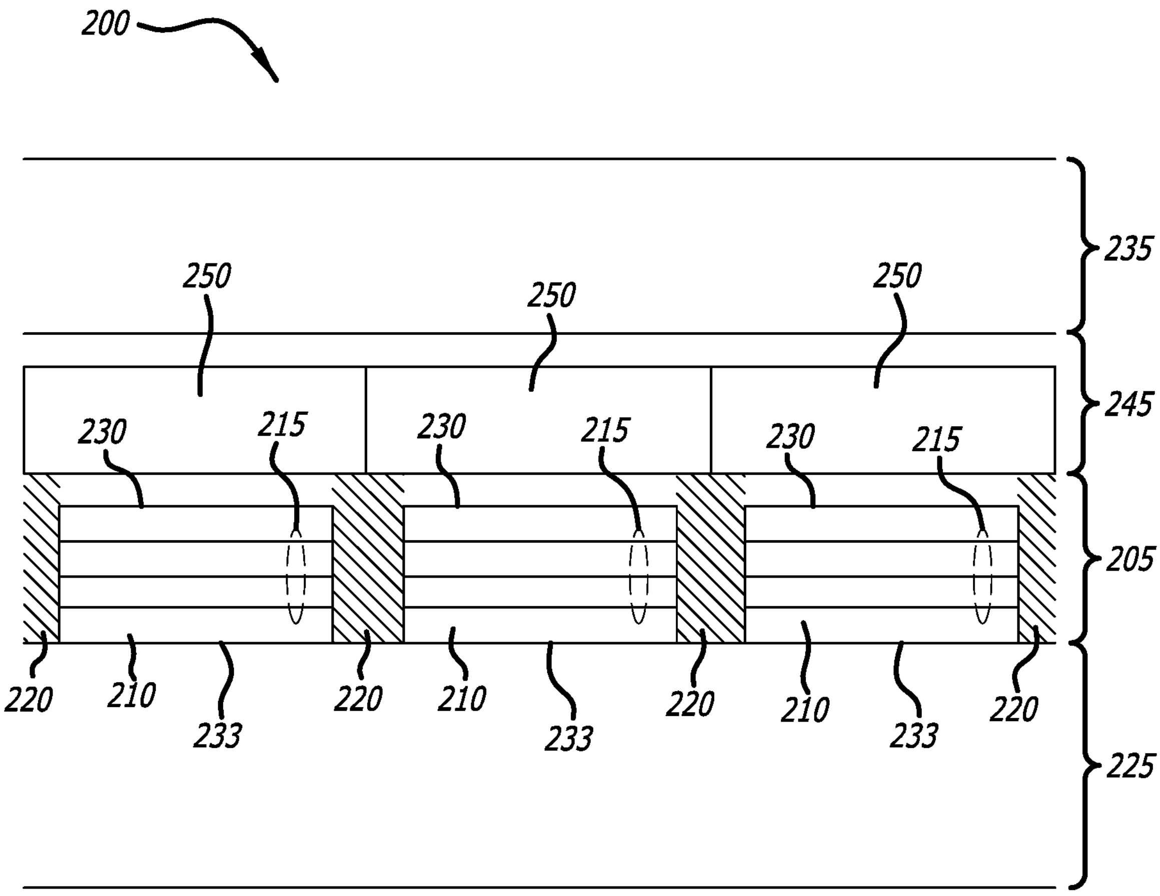

z
y
x
Multiview pixel
Guided light
$n_{eff}$
$\theta_{in}$
$\phi$

FIG. 1F


200
235
250
250
250
245
230
215
230
215
230
215
205
220
210
233
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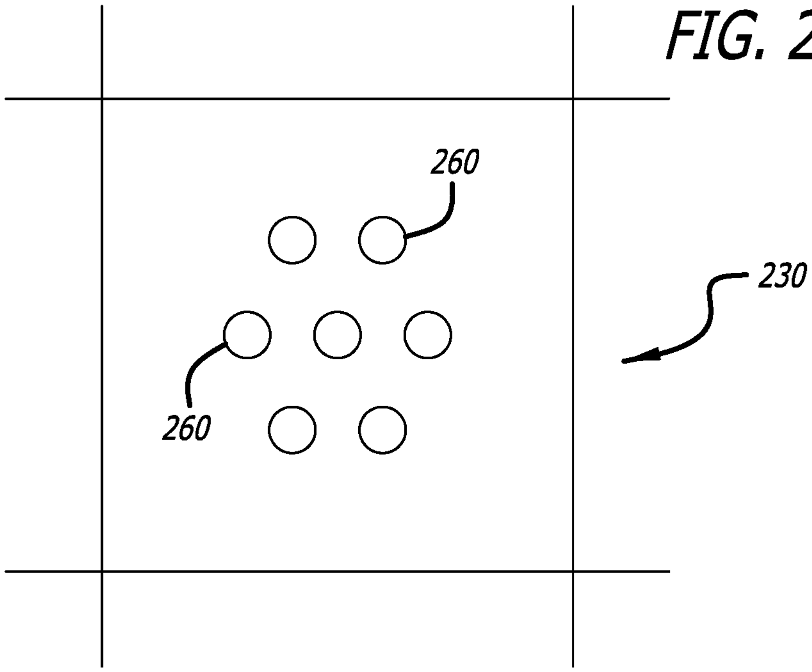
210
233
220
210
233
220
225

FIG. 2A

FIG. 2B-1



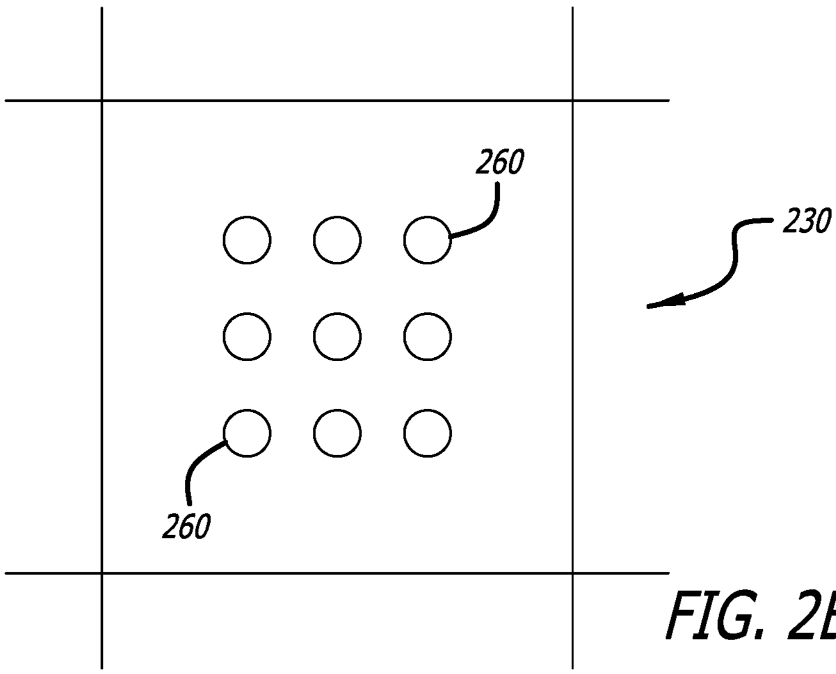




FIG. 2B-2

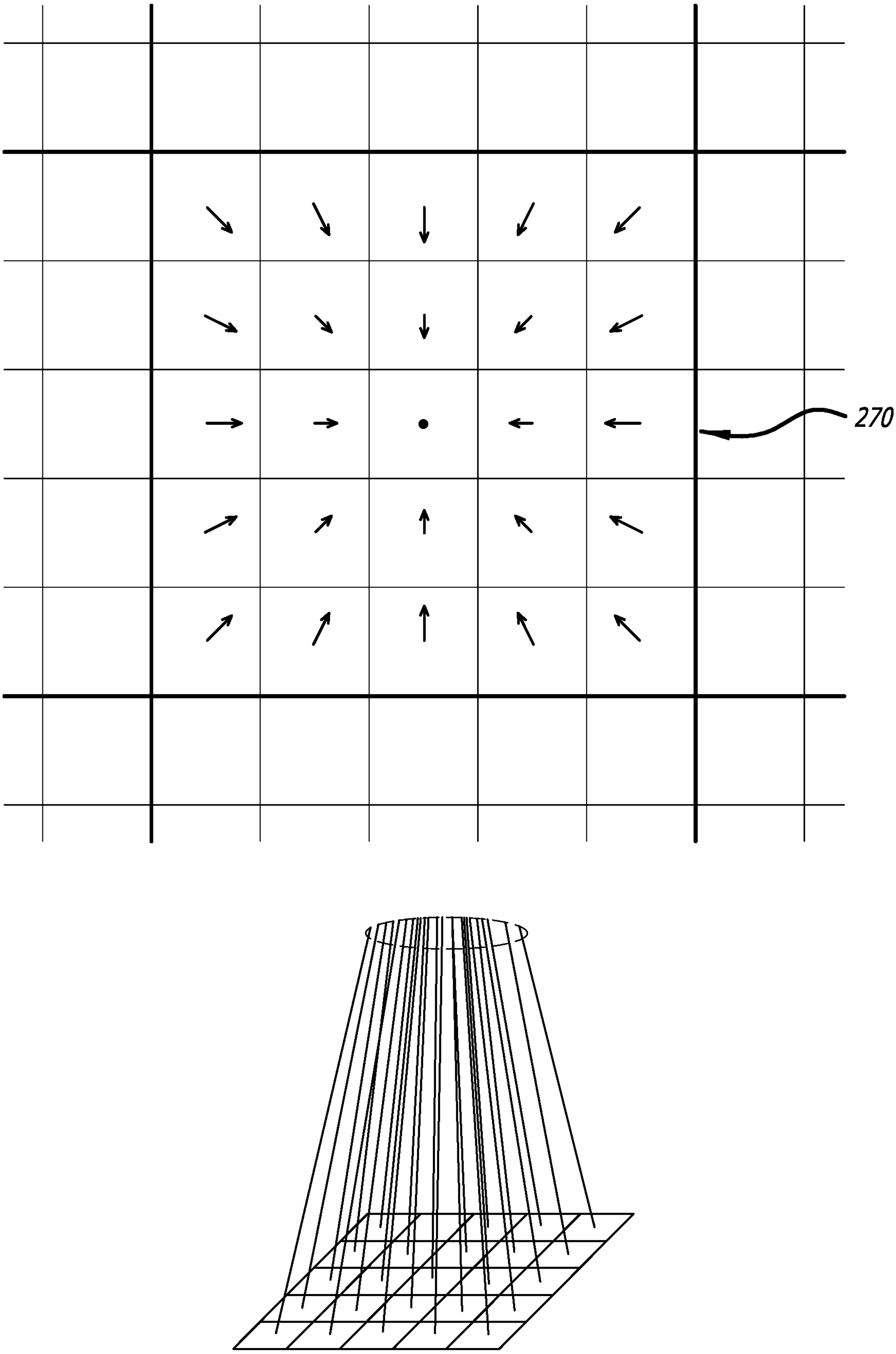



FIG. 2C-1

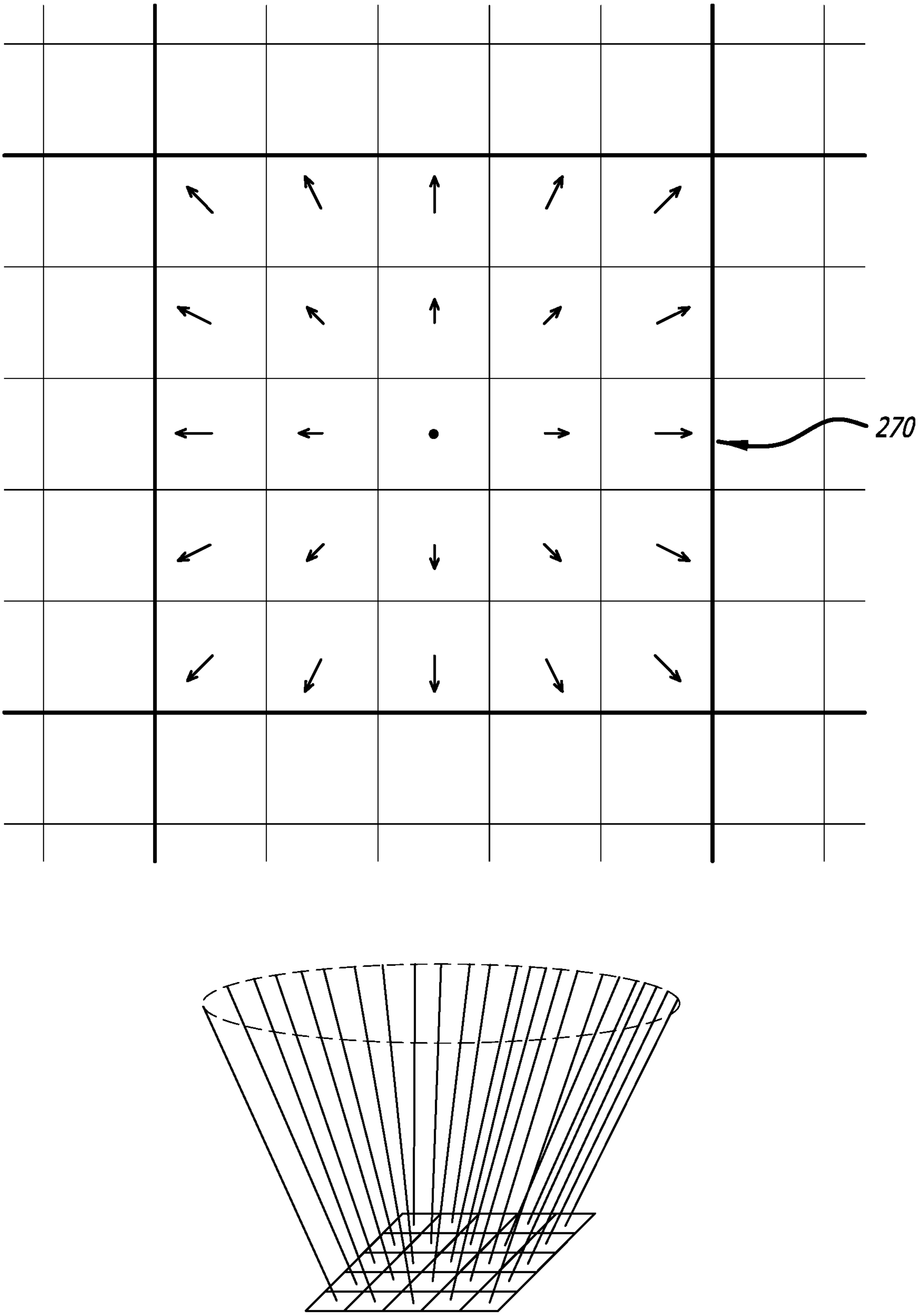



FIG. 2C-2

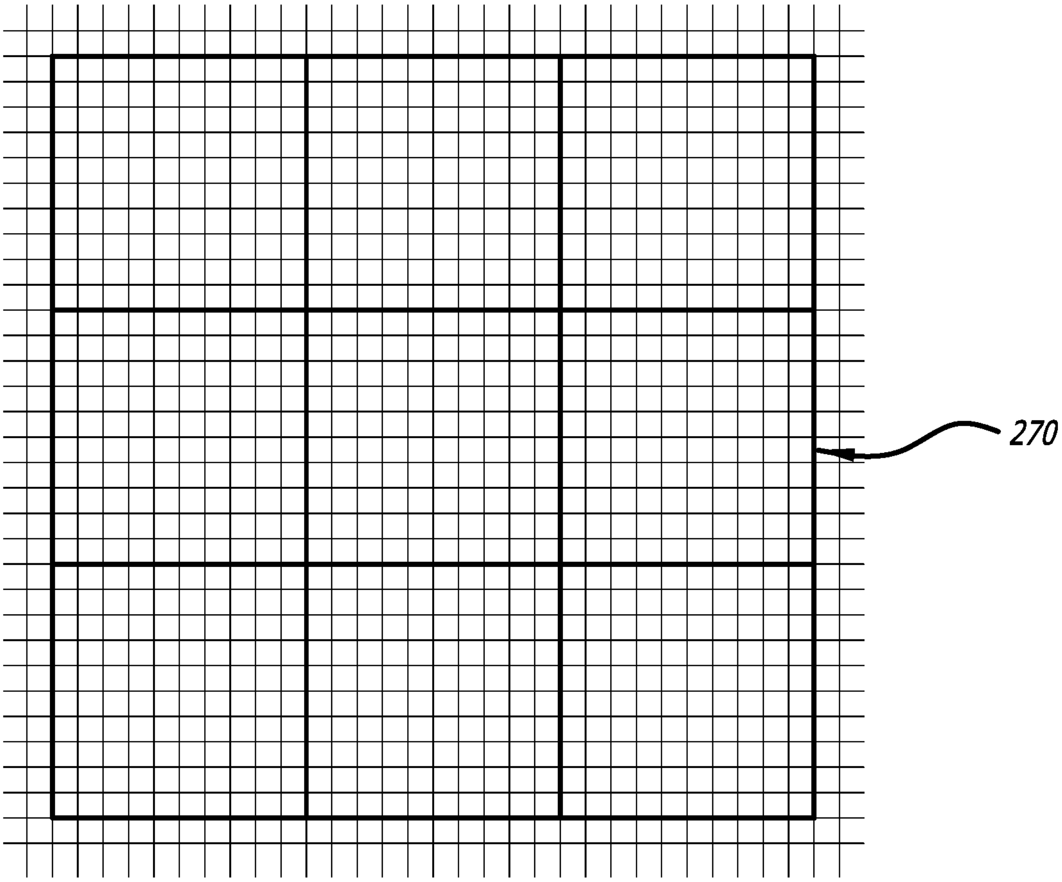
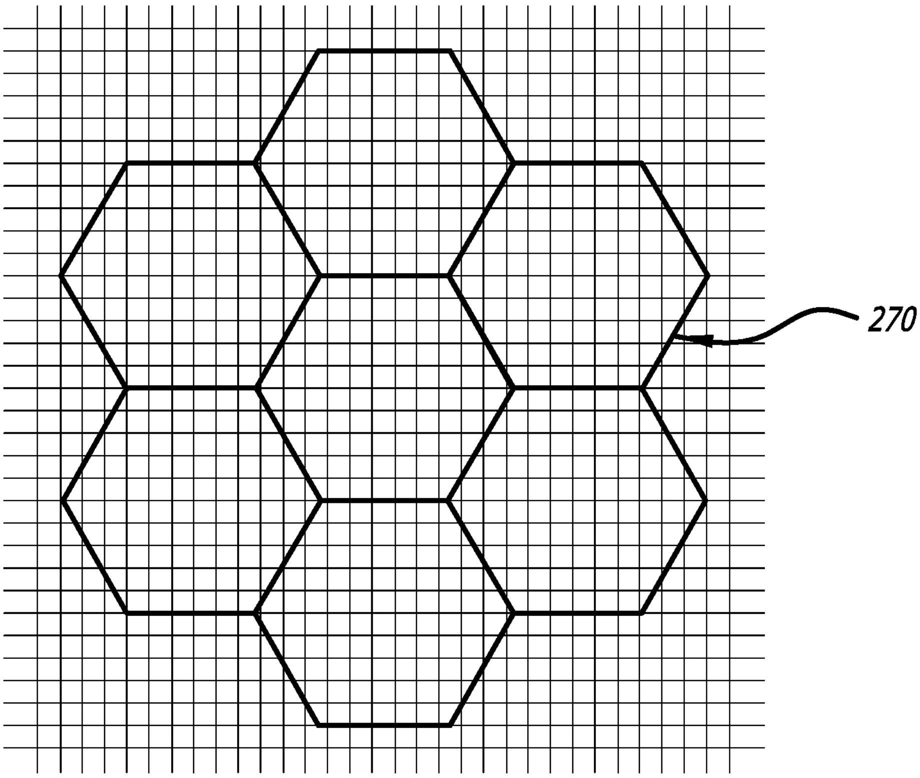



FIG. 2D-1

FIG. 2D-2



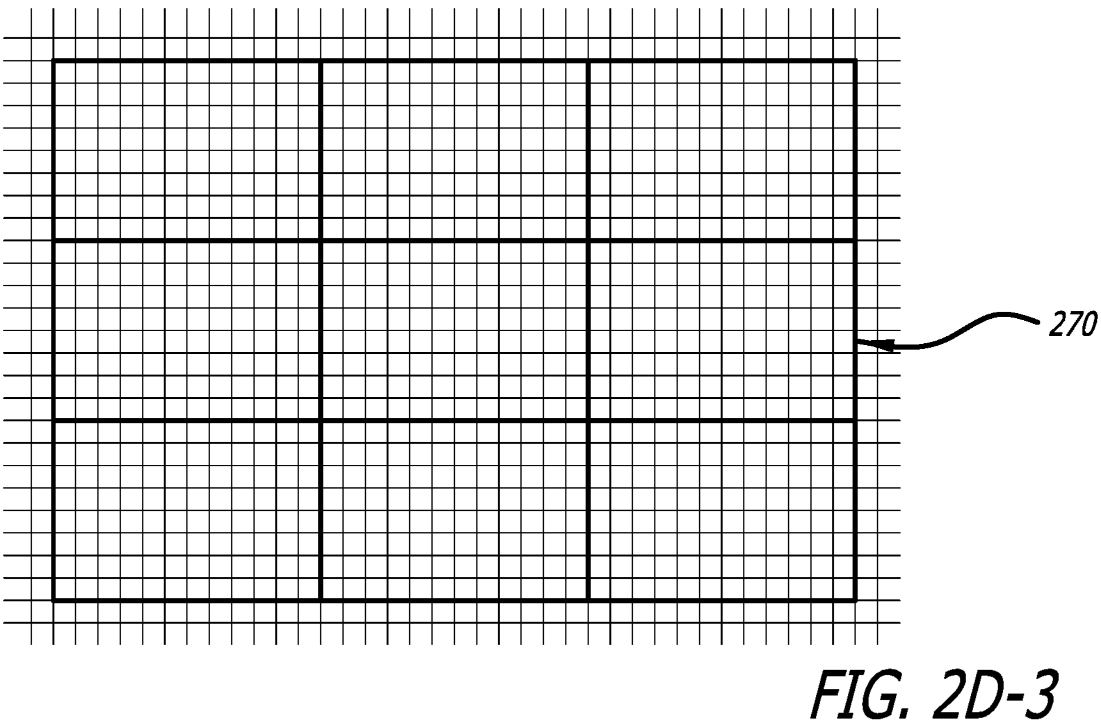
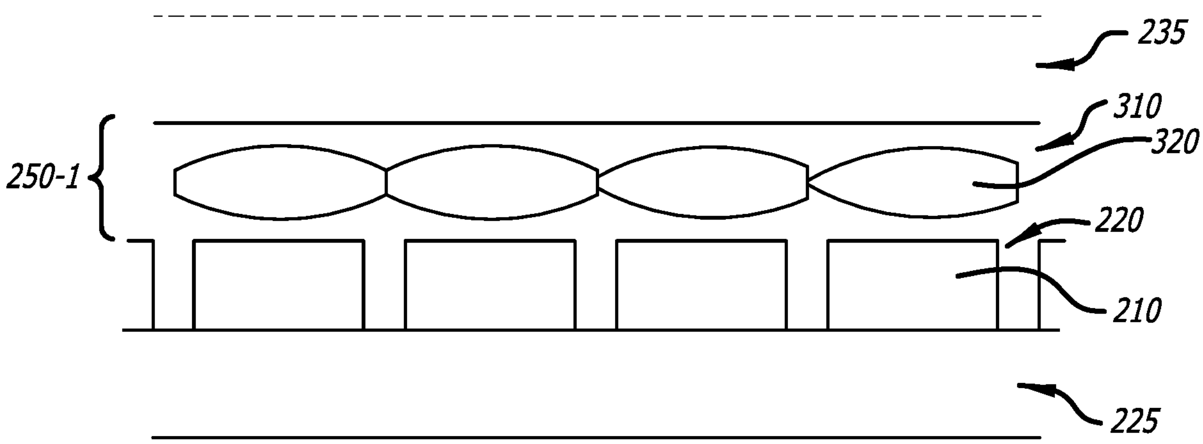




FIG. 2D-3

FIG. 3A



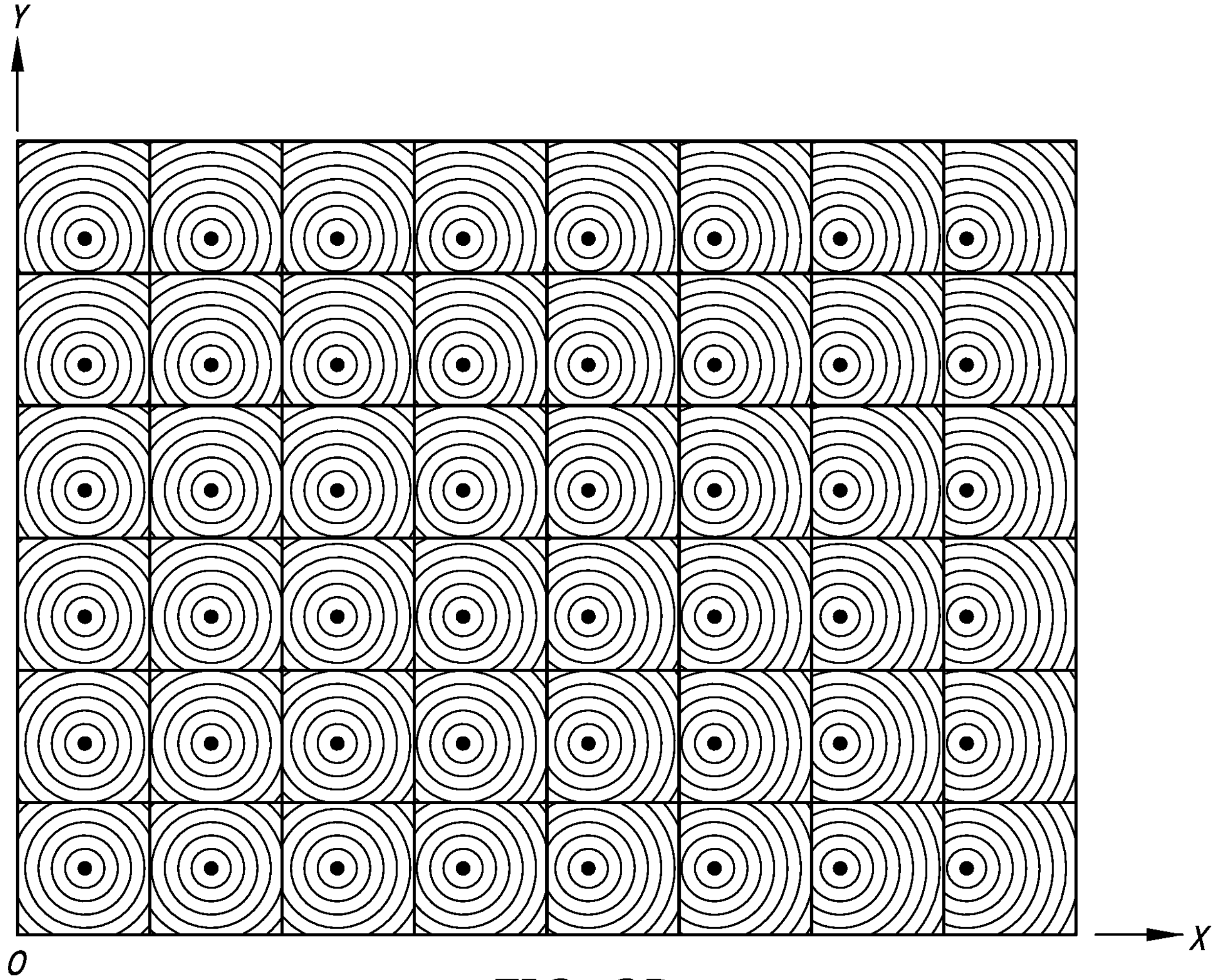
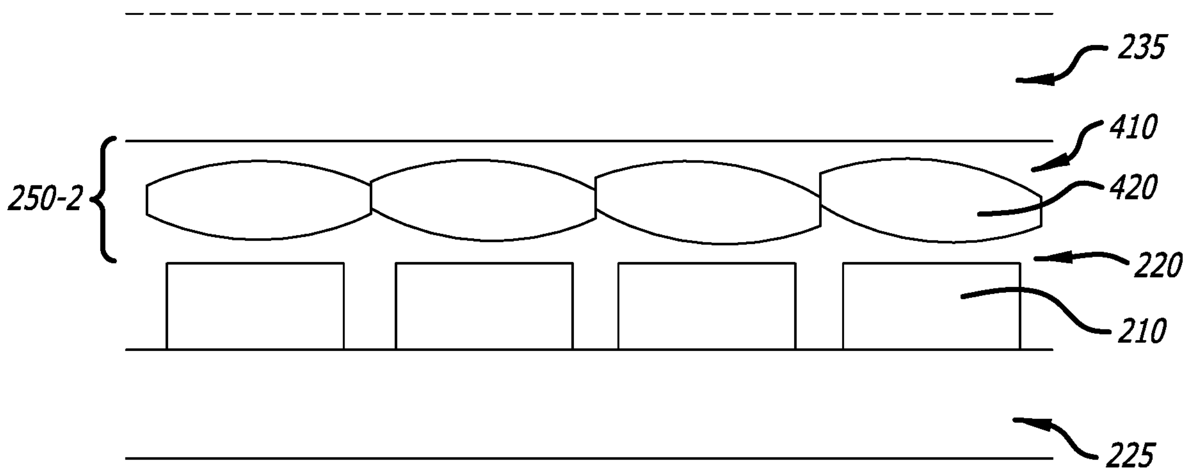




FIG. 3B

FIG. 4A



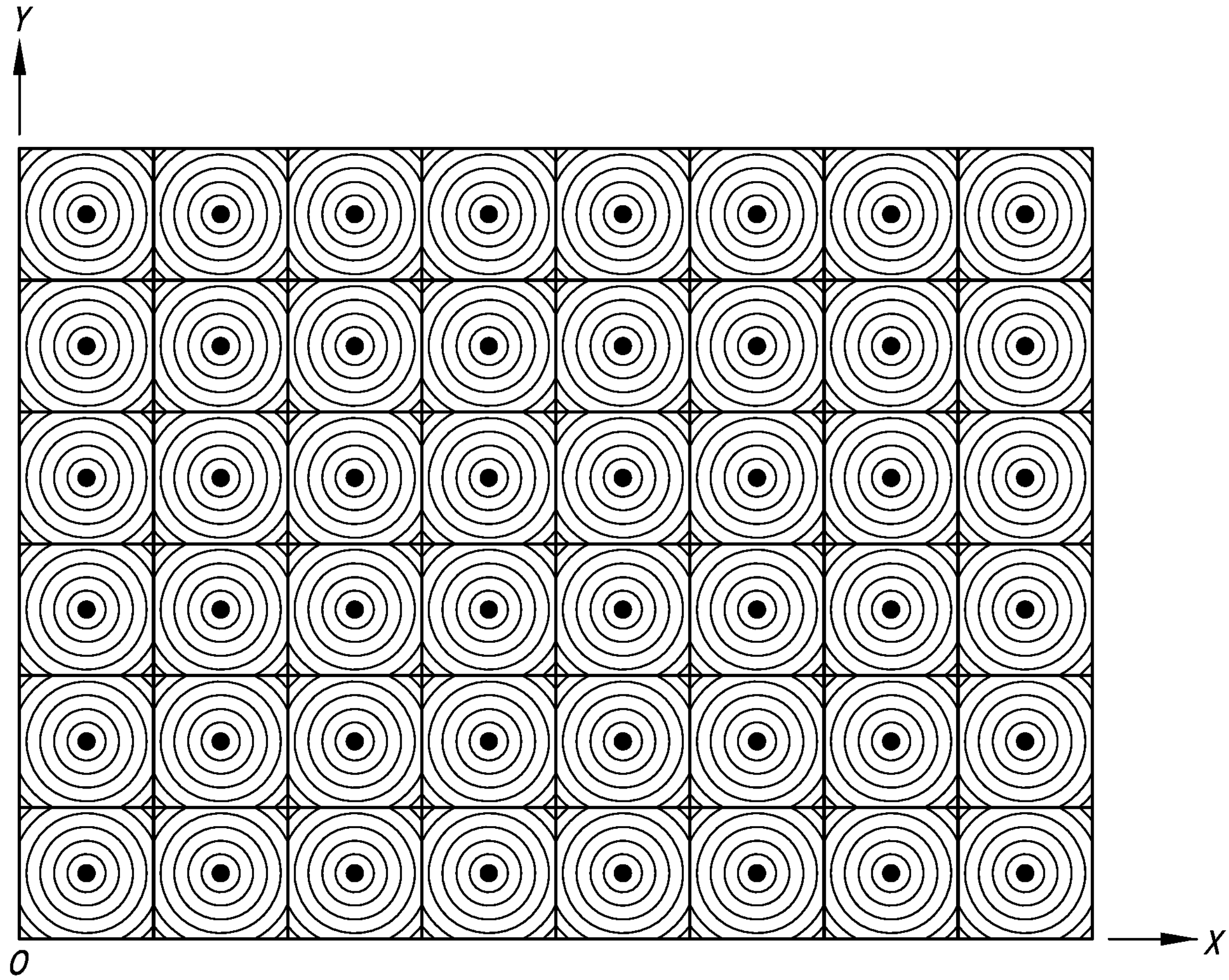
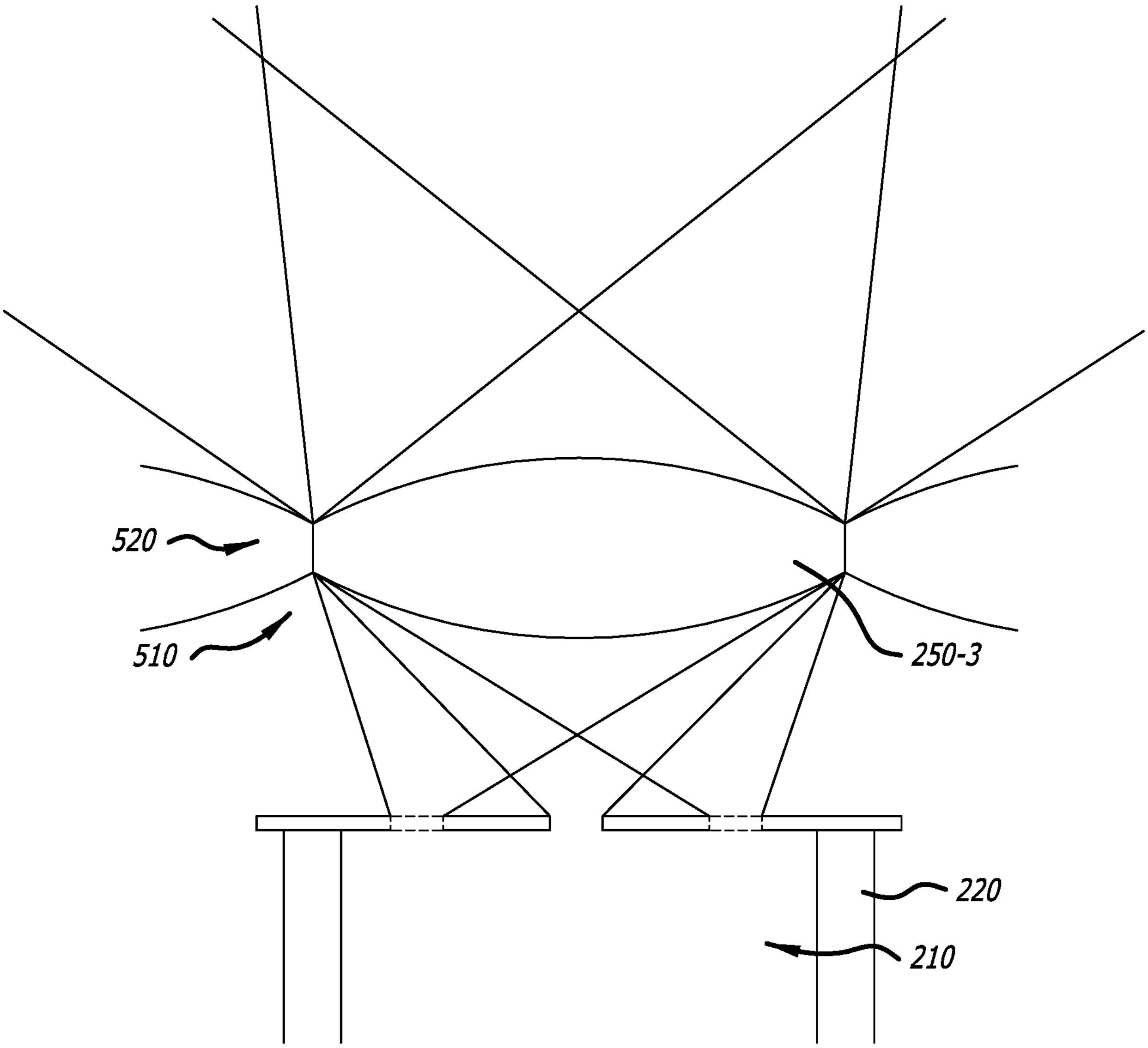




FIG. 4B

FIG. 5A



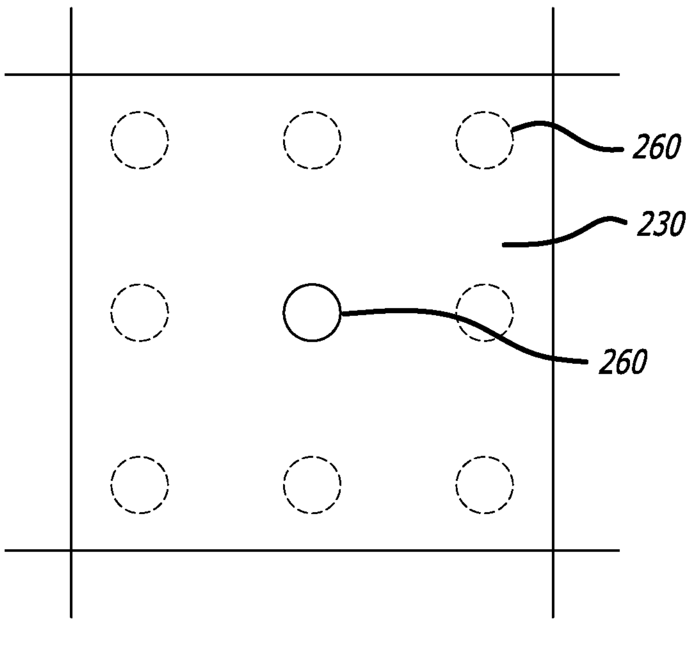




FIG. 5B

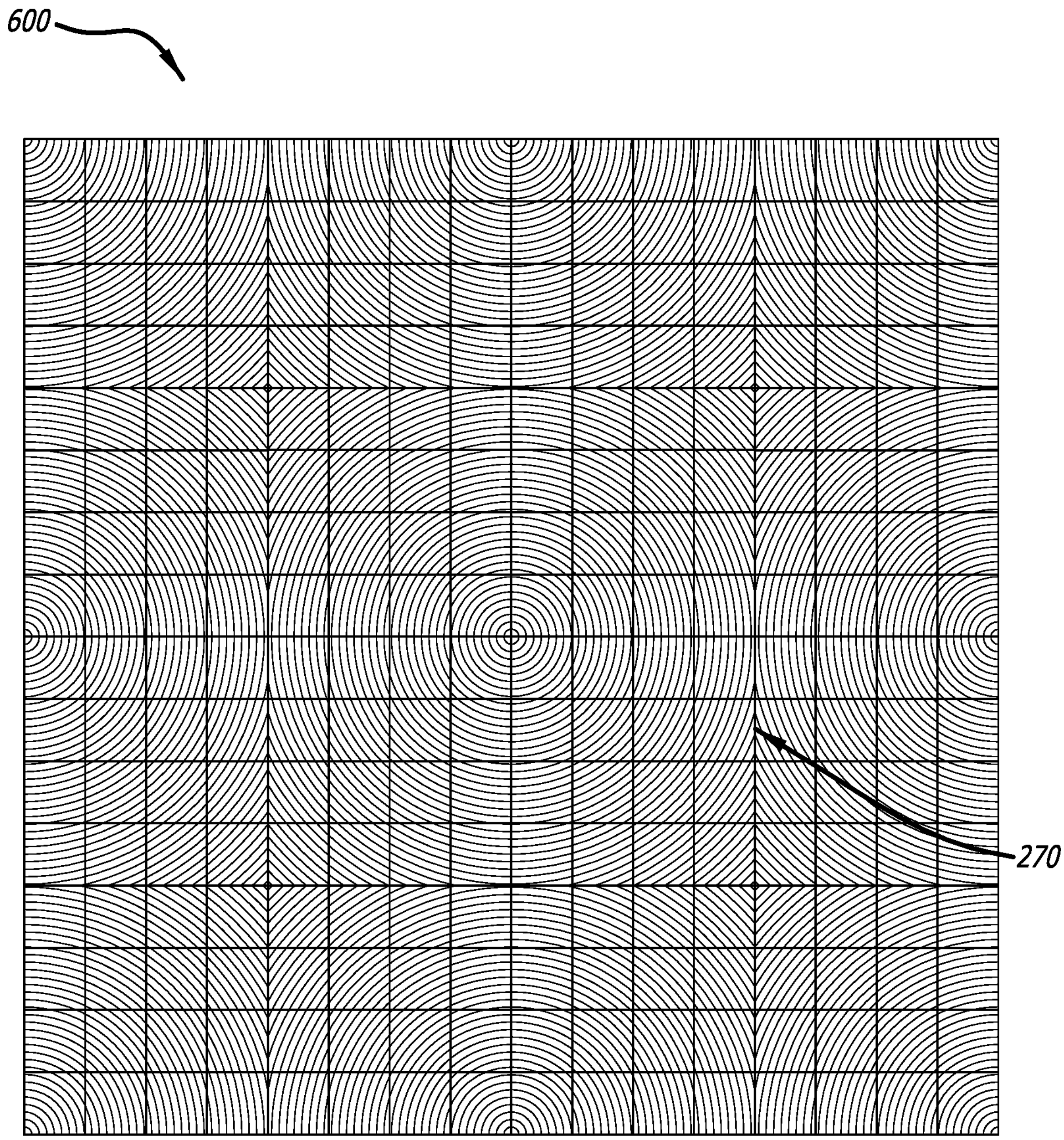



FIG. 6A

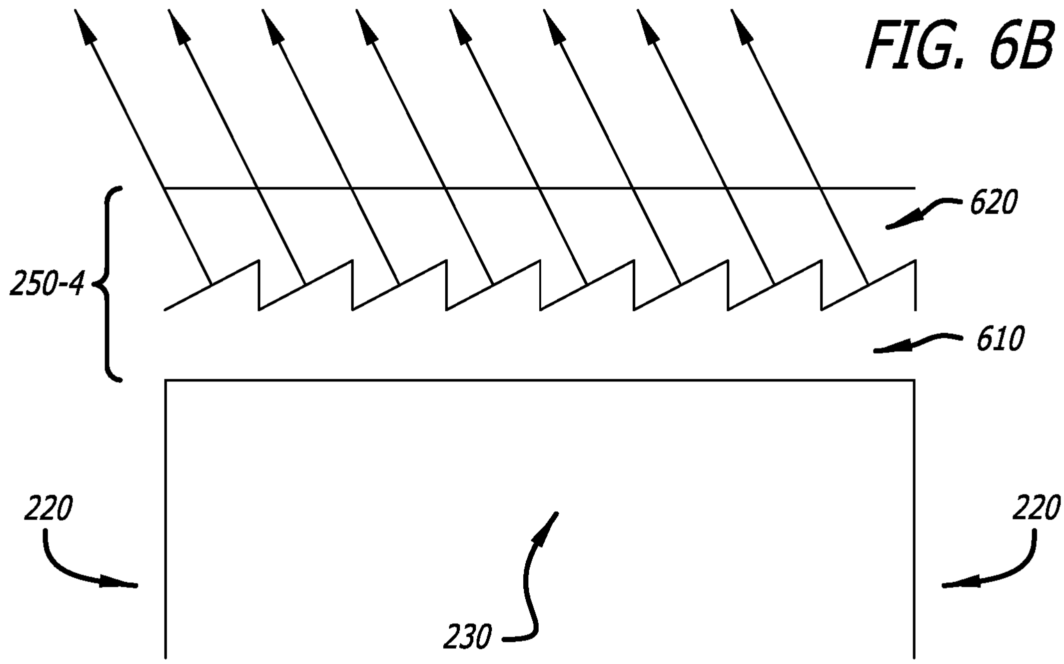



FIG. 6B

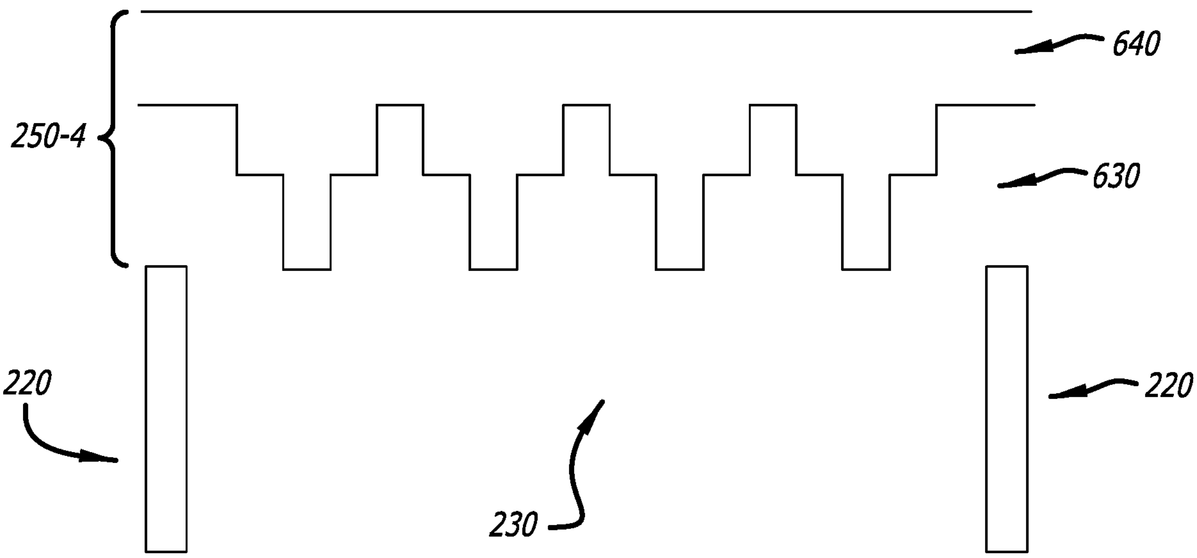



FIG. 6C

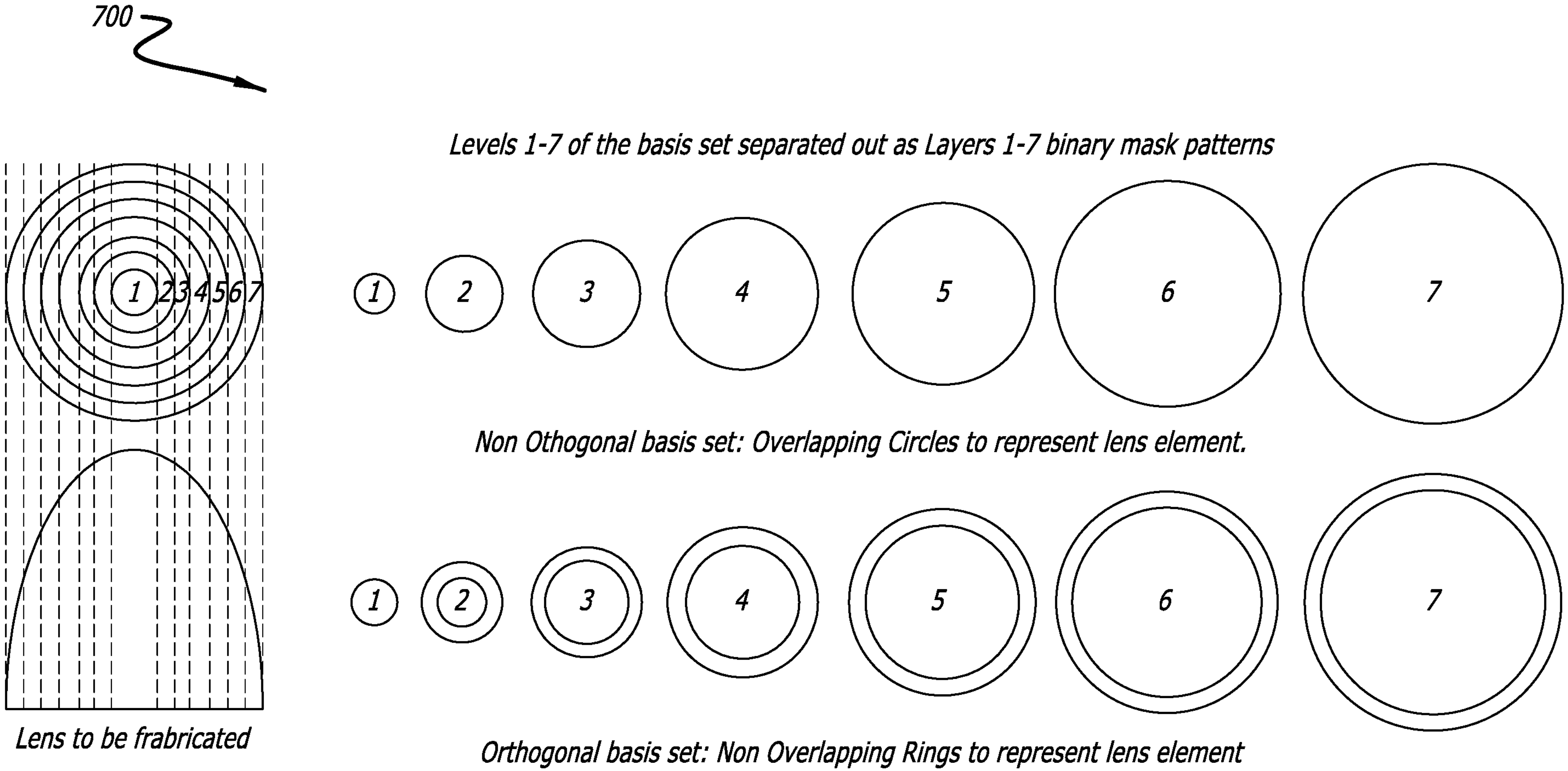

700
Levels 1-7 of the basis set separated out as Layers 1-7 binary mask patterns
1234567
1
2
3
4
5
6
7
Non Othogonal basis set: Overlapping Circles to represent lens element.
1
2
3
4
5
6
7
Orthogonal basis set: Non Overlapping Rings to represent lens element
Lens to be frabricated

FIG. 7A

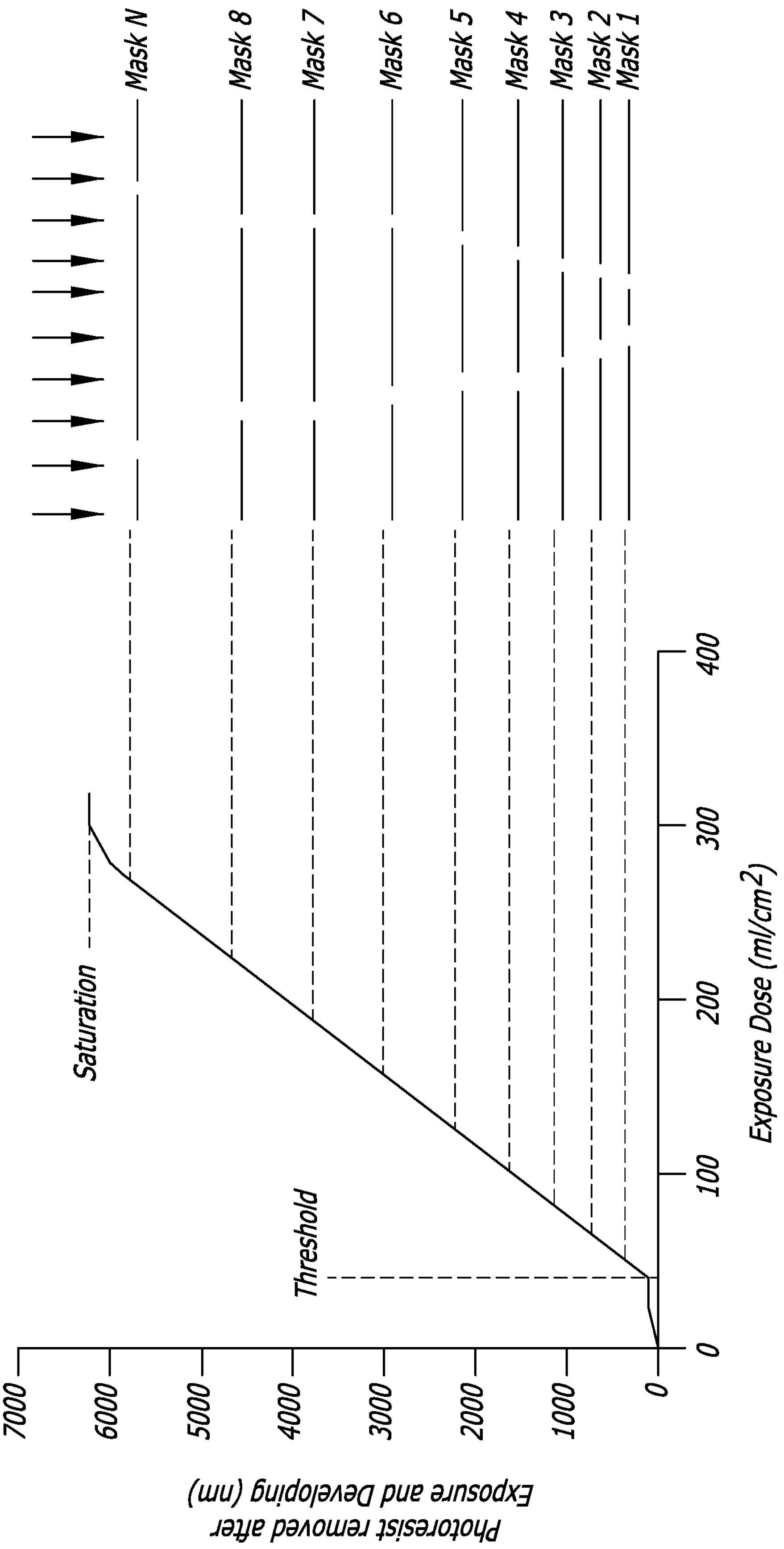

Photoresist removed after Exposure and Developing (nm)
7000
6000
5000
4000
3000
2000
1000
0
Exposure Dose (ml/cm²)
0
100
200
300
400
Threshold
Saturation
Mask N
Mask 8
Mask 7
Mask 6
Mask 5
Mask 4
Mask 3
Mask 2
Mask 1

FIG. 7B

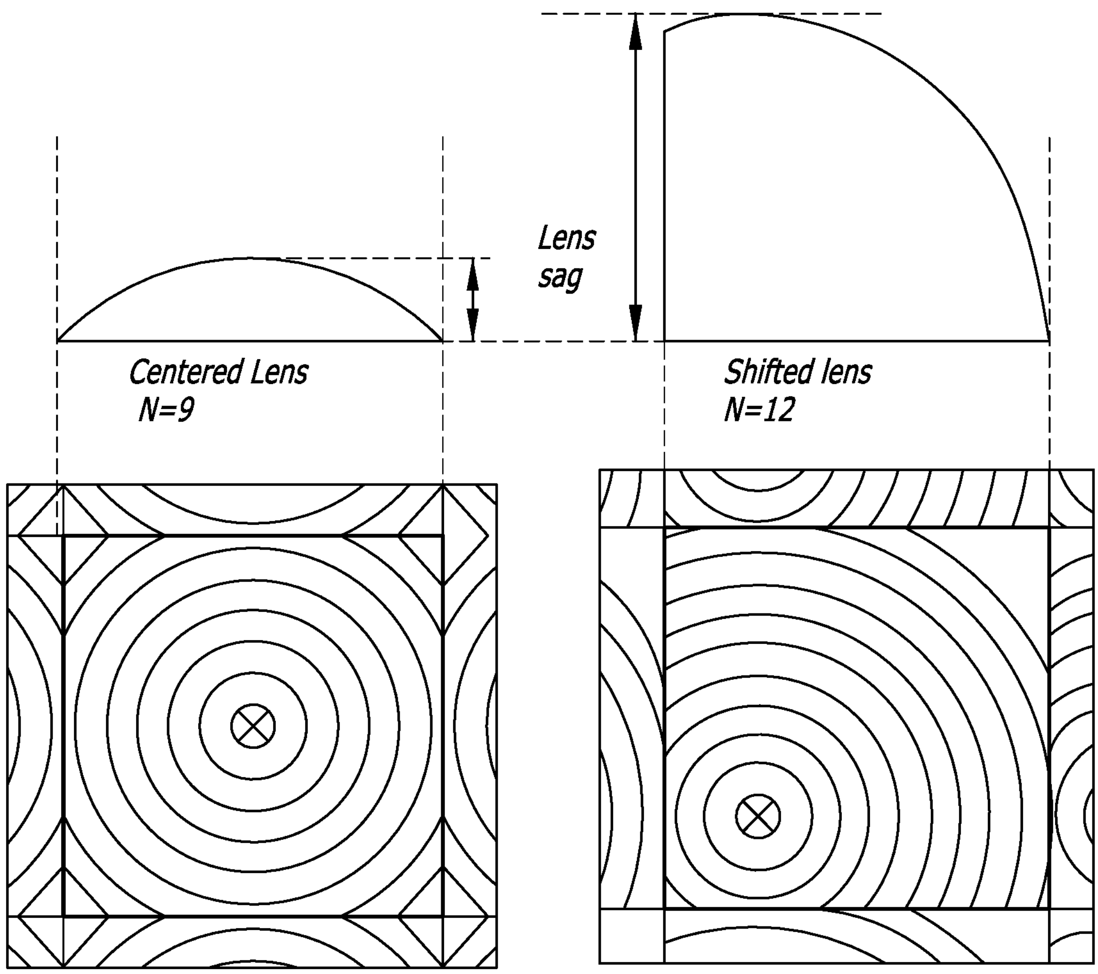



FIG. 7C

FIG. 7D

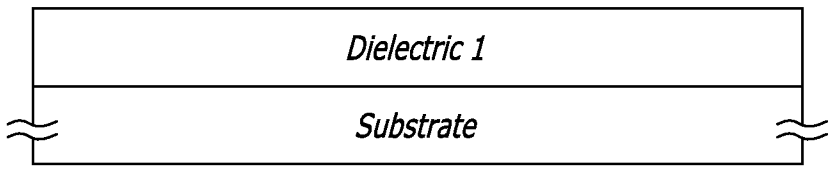



FIG. 7E

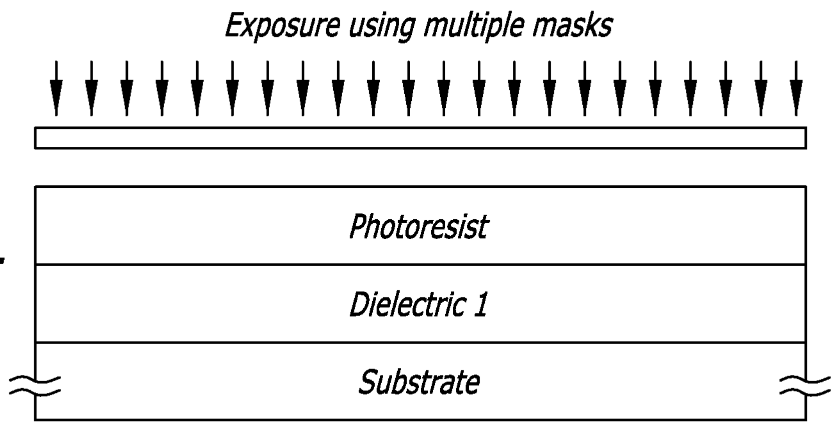



FIG. 7F

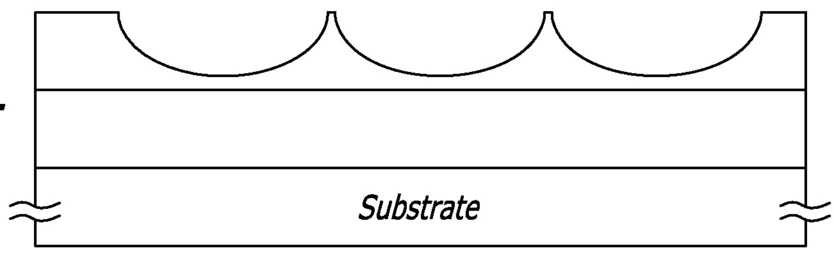


FIG. 7G

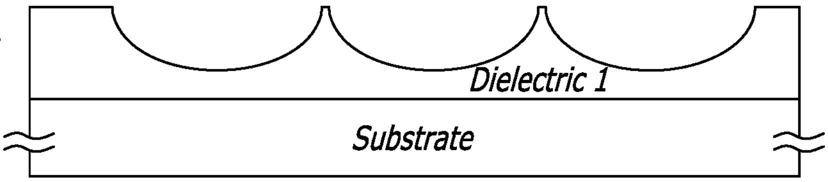



FIG. 7H

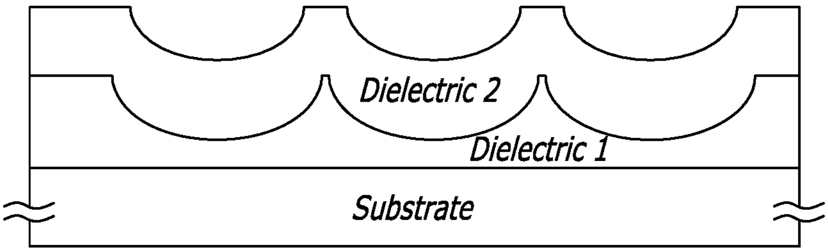
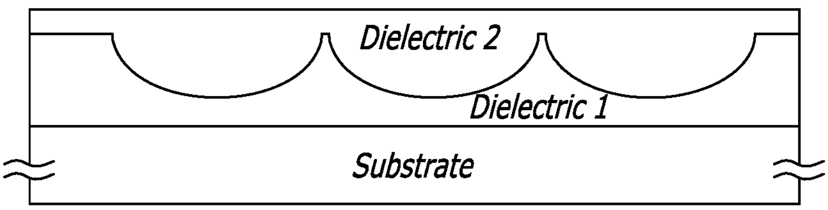



FIG. 7I



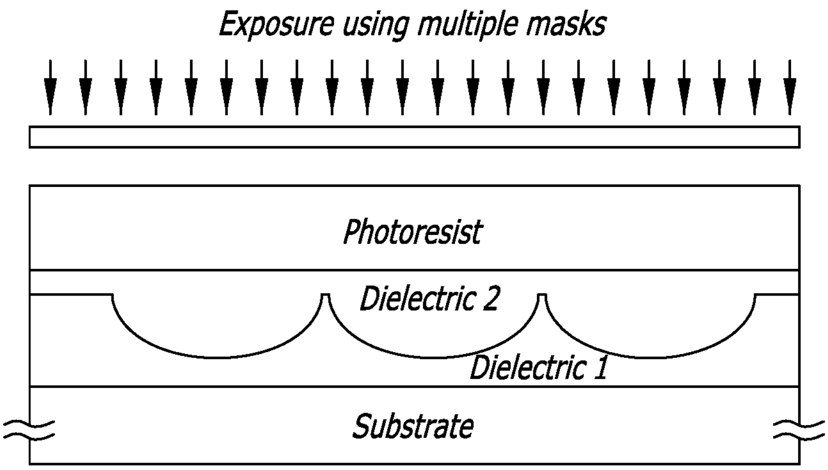

Exposure using multiple masks
Photoresist
Dielectric 2
Dielectric 1
Substrate

FIG. 7J

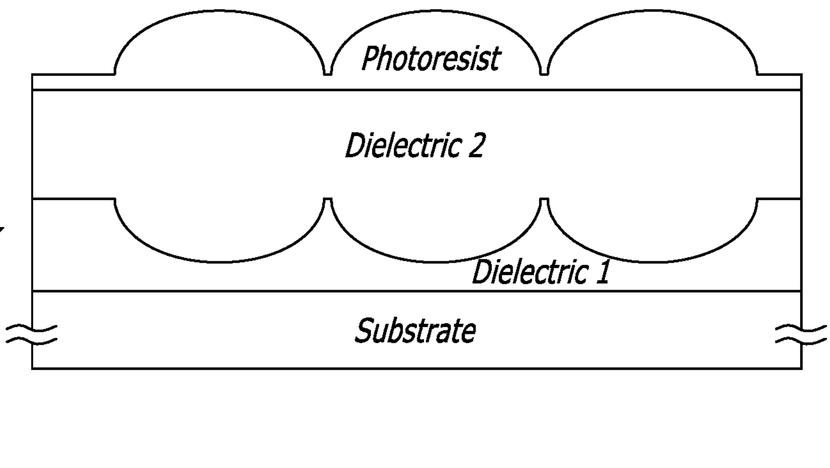

Photoresist
Dielectric 2
Dielectric 1
Substrate

FIG. 7K

FIG. 7L

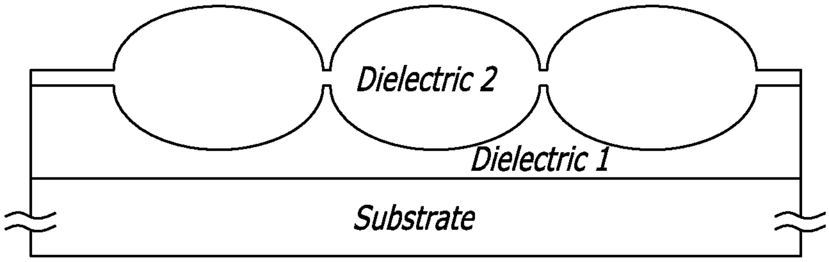
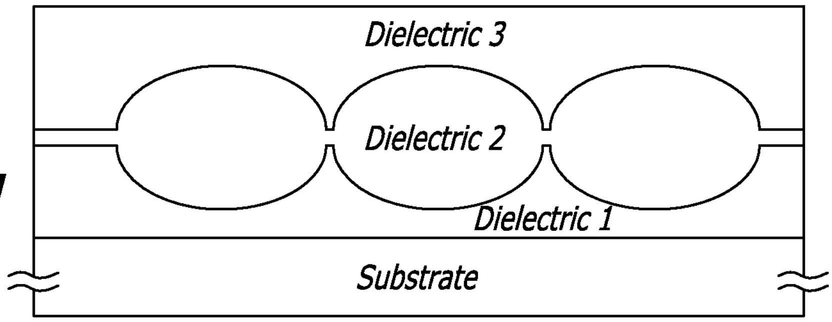

Dielectric 2
Dielectric 1
Substrate

FIG. 7M


Dielectric 3
Dielectric 2
Dielectric 1
Substrate

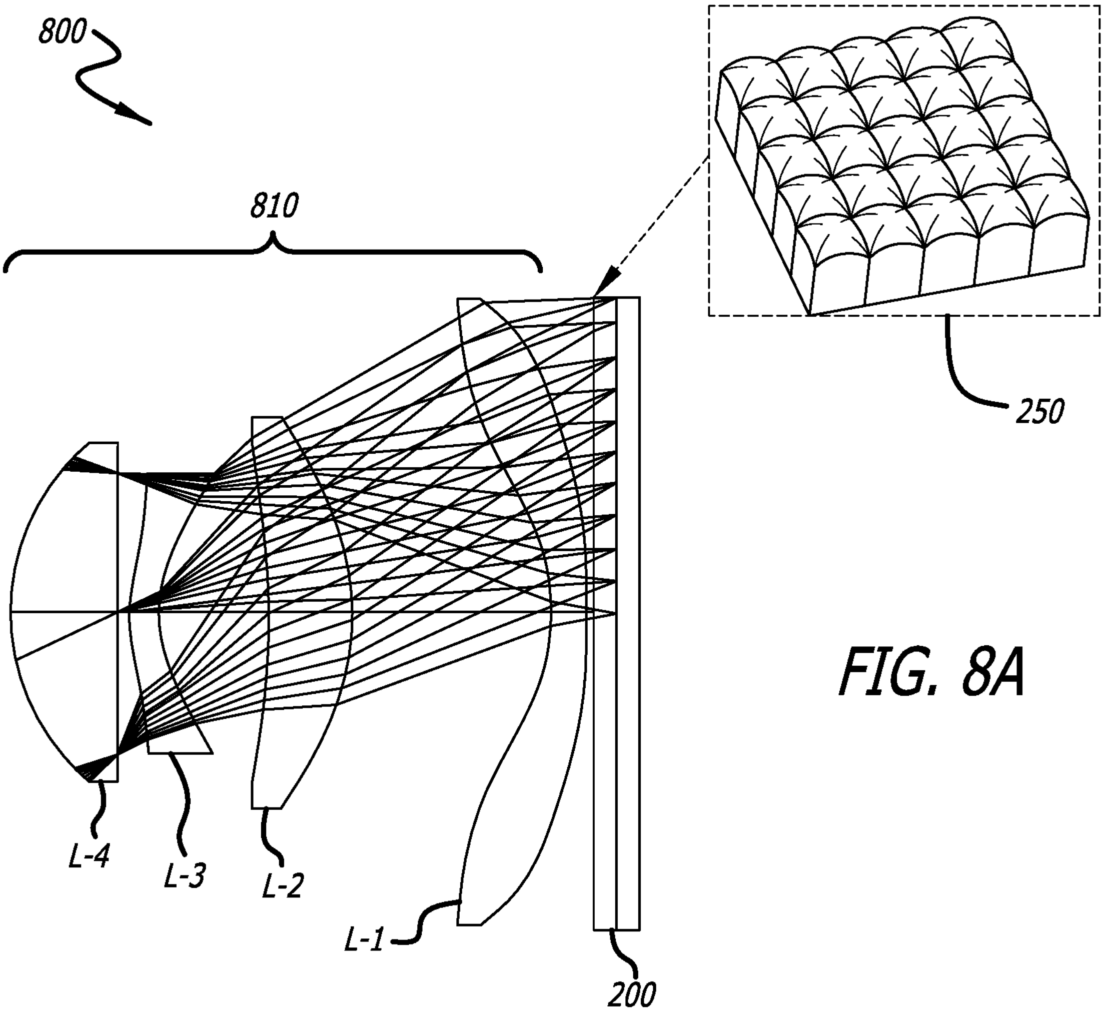



FIG. 8A

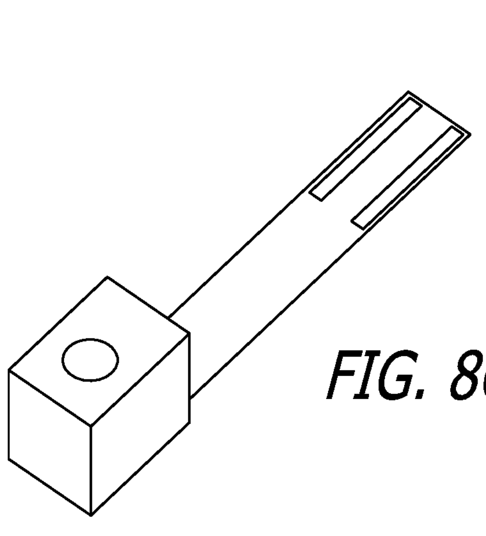
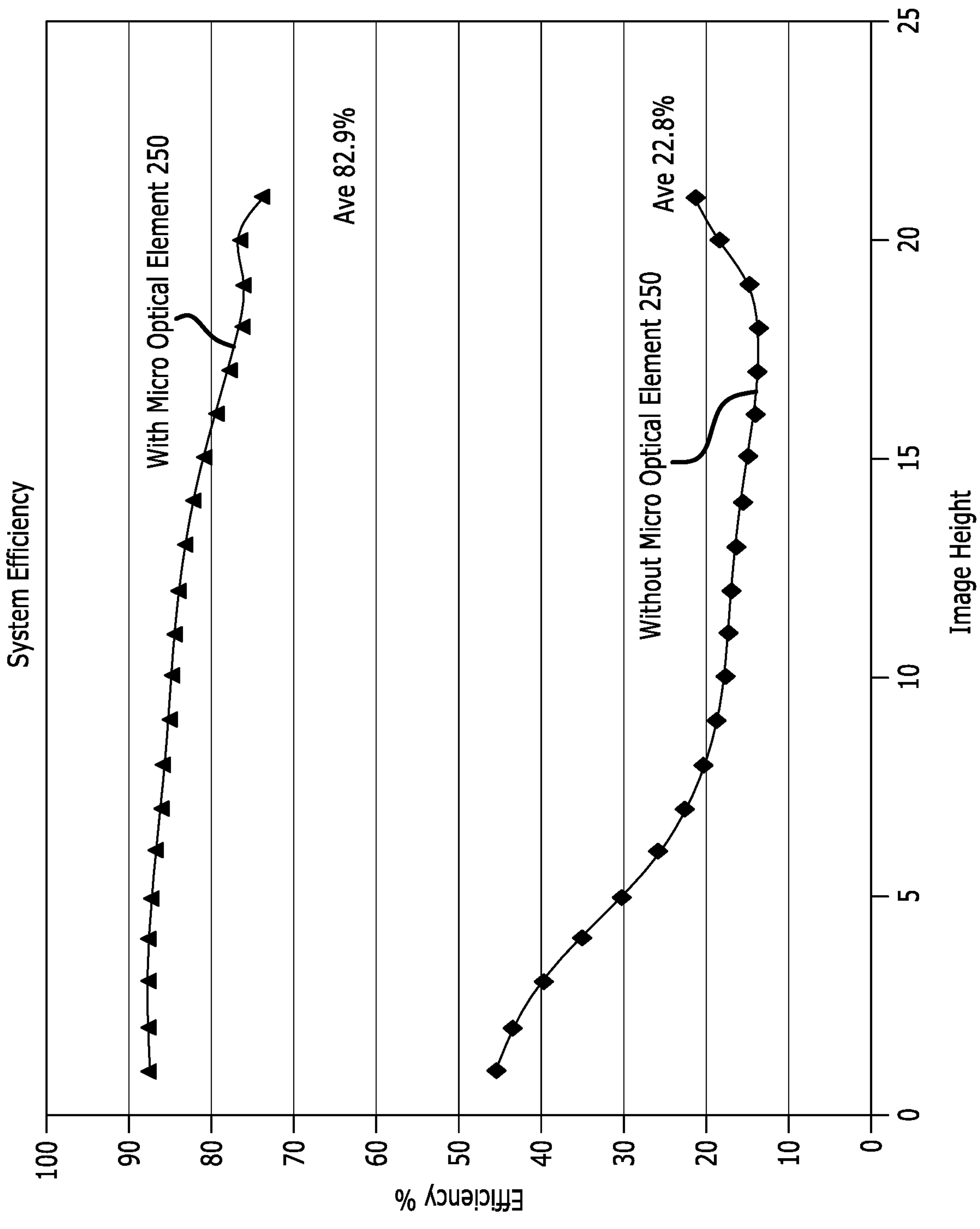


FIG. 8C

FIG. 8B


System Efficiency
With Micro Optical Element 250
Ave 82.9%
Without Micro Optical Element 250
Ave 22.8%
Efficiency %
Image Height
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25

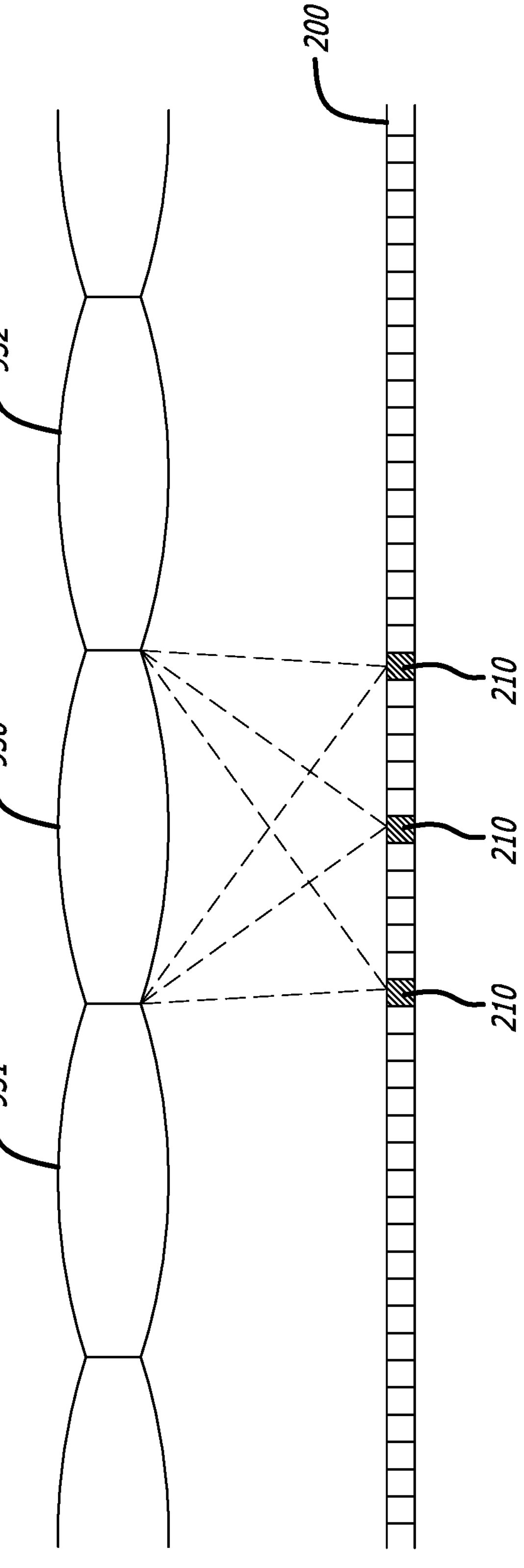



FIG. 9

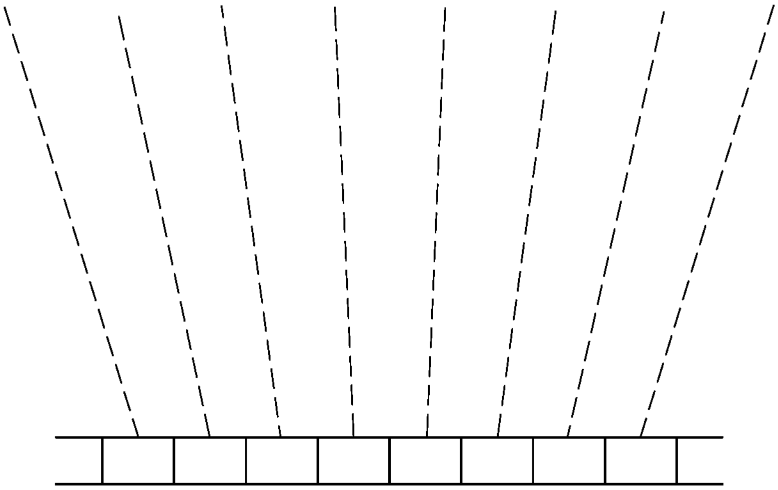


FIG. 10B

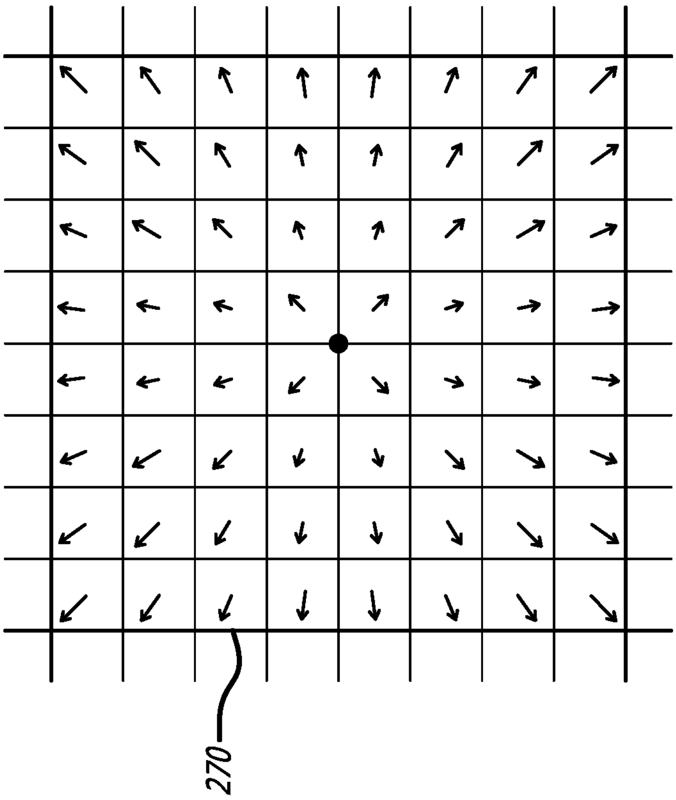



FIG. 10A

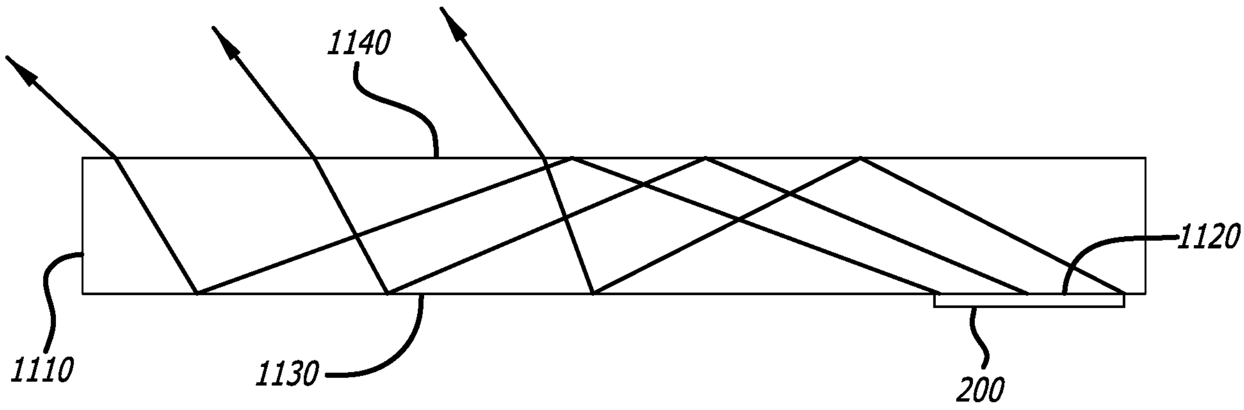



FIG. 11A

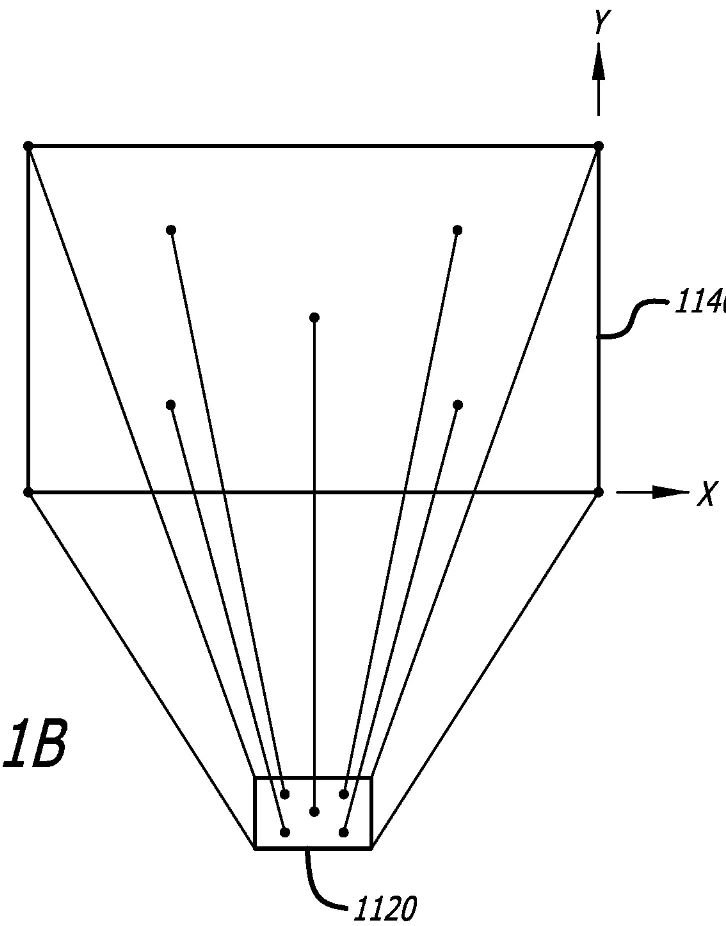



FIG. 11B

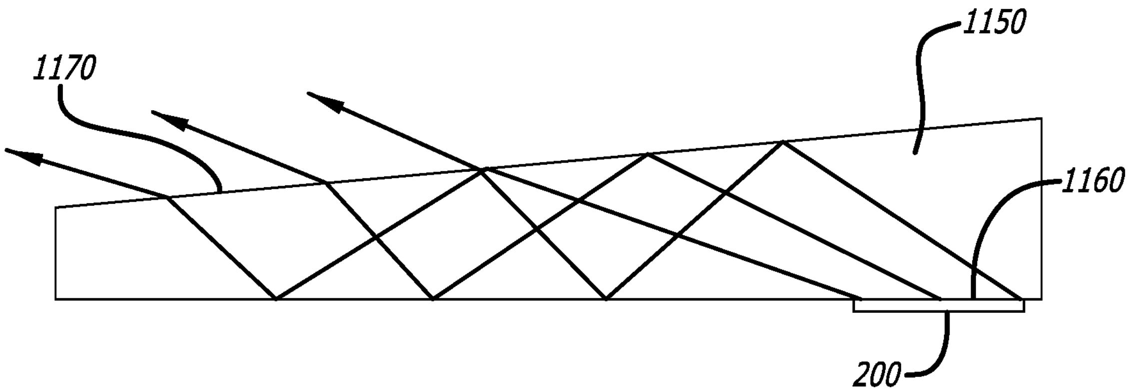



FIG. 11C

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/069042

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G09G 3/34; H01L 29/18; H01L 29/20; H01L 33/00 (2017.01)
CPC - G09G 3/346; H01L 25/0753; H01L 33/32; H01L 33/504 (2017.02)

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)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 257/86, 88, 89; 345/84; 438/24, 32, 35 (keyword delimited)

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | US 2009/0278998 A1 (EL-GHOROURY et al) 12 November 2009 (12.11.2009) entire document | 1-29 |
| Y | US 2014/0055692 A1 (KROLL et al) 27 February 2014 (27.02.2014) entire document | 1-29 |
| Y | US 2006/0132383 A1 (GALLY et al) 22 June 2006 (22.06.2006) entire document | 2, 3 |
| Y | US 2015/0277126 A1 (SONY CORPORATION) 01 October 2015 (01.10.2015) entire document | 8, 9, 17, 23-25 |
| Y | US 2009/0073559 A1 (WOODGATE et al) 19 March 2009 (19.03.2009) entire document | 10 |
| Y | US 2013/0258451 A1 (EL-GHOROURY et al) 03 October 2013 (03.10.2013) entire document | 20, 21 |
| Y | US 2007/0052694 A1 (HOLMES) 08 March 2007 (08.03.2007) entire document | 22 |
| Y | US 2004/0240064 A1 (DUTTA) 02 December 2004 (02.12.2004) entire document | 24 |
| Y | US 2002/0008854 A1 (LEIGH TRAVIS) 24 January 2002 (24.01.2002) entire document | 28 |
| Y | US 2012/0288995 A1 (EL-GHOROURY HUSSEIN S et al) 15 November 2012 (15.11.2012) entire document | 29 |
| A | US 2004/0080938 A1 (HOLMAN et al) 29 April 2004 (29.04.2004) entire document | 1-29 |
| A | US 2013/0083303 A1 (HOOVER et al) 04 April 2013 (04.04.2013) entire document | 1-29 |

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 03 April 2017 | 19 APR 2017 |

| Name and mailing address of the ISA/US | Authorized officer |
|---|---|
| Mail Stop PCT, Attn: ISA/US, Commissioner for Patents<br>P.O. Box 1450, Alexandria, VA 22313-1450<br>Facsimile No. 571-273-8300 | Blaine R. Copenheaver<br>PCT Helpdesk: 571-272-4300<br>PCT OSP: 571-272-7774 |

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/069042

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:
See Extra Sheet(s)

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-29

**Remark on Protest**

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-29, drawn to a method of making a non-telecentric emissive micro-pixel array light modulator.
Group II, claims 1-28,30, drawn to a method of fabricating an ultra compact display projector.
Group III, claims 1-28,31,34, drawn to a method of fabricating a minimum cross-talk light field modulator.
Group IV, claims 32-33, drawn to a method for guiding an image comprising of a plurality of pixel outputs in a total internal reflection waveguide.

The inventions listed as Groups I, II, III or IV do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: bonding the directional modulation layer to the pixelated, multiple color emission III/V semiconductor layer stack as already bonded to the CMOS control layer, or bonding the pixelated, multiple color emission III/V semiconductor layer stack to a CMOS control layer as claimed therein is not present in the invention of Groups II, III or IV. The special technical feature of the Group II invention: one or more additional optical elements for receiving light from the second optical element to magnify a projected image, the optical elements directionally modulating the light emitted to achieve maximum fill factor of the optical aperture of the first optical element, the first optical element redirecting the light rays toward an optical aperture the second optical element while maintaining the fill factor at a maximum, the second optical element redirecting the light to the one or more additional optical elements for receiving light from the second optical element to magnify the projected image as claimed therein is not present in the invention of Groups I, III or IV. The special technical feature of the Group III invention: layer such that the light from the optical elements remains substantially confined within optical apertures of associated hogel lens apertures, thus minimizing the light leakage or cross-talk between adjacent the hogel lenses as claimed therein is not present in the invention of Groups I, II or IV. The special technical feature of the Group IV invention: directionally modulate the respective imager pixel outputs in a total internal reflection waveguide in a unique direction within a tangential or lateral, and a vectorial or elevation plane, to define a waveguiding angle of the imager pixel outputs and a lateral divergence from a respective pixel's (x,y) coordinates as claimed therein is not present in the invention of Groups I, II or III.

Groups I, II, III, and IV lack unity of invention because even though the inventions of these groups require the technical feature of pixelated, multiple color emission III/V semiconductor layers stacked above the control layer and controllable from the control layer to emit at least partially collimated, pixelated light that is modulated chromatically and temporally; and a directional modulation layer of optical elements above the pixelated multiple color emission III/V semiconductor layers, each optical element to directionally modulate light, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2013/0258451 A1 (EL-GHOROURY et al) 03 October 2013 (03.10.2013) teaches pixelated, multiple color emission III/V semiconductor layers stacked above the control layer and controllable from the control layer to emit at least partially collimated, pixelated light that is modulated chromatically and temporally (Paras. 30 and 34); and a directional modulation layer of optical elements above the pixelated multiple color emission III/V semiconductor layers, each optical element to directionally modulate light (Paras. 32-33).

Since none of the special technical features of the Group I, II, III, or IV inventions are found in more than one of the inventions, unity of invention is lacking.