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(54) **Title:** SPATIO-OPTICAL AND TEMPORAL SPATIO-OPTICAL DIRECTIONAL LIGHT MODULATORS

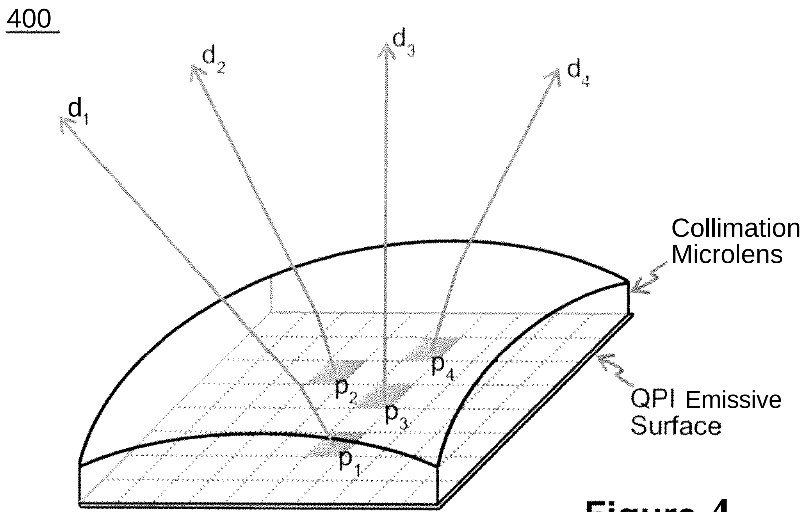

Figure 4

(57) **Abstract:** Spatio-optical directional light modulators and temporal spatio-optical directional light modulators are introduced. These directional light modulators can be used to create 3D displays, ultra-high resolution 2D displays or 2D/3D switchable displays with extended viewing angle. The temporal spatio-optical aspects of an embodiment of these novel light modulators allow them to modulate the intensity, color and direction of the light they emit within a wide viewing angle. The inherently fast modulation and wide angular coverage capabilities of these directional light modulators increase the achievable viewing angle, and directional resolution making the 3D images created by the display be more realistic or alternatively the 2D images created by the display having ultra high resolution. Alternate embodiments are disclosed.

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SPATIO-OPTICAL AND TEMPORAL SPATIO-OPTICAL DIRECTIONAL LIGHT MODULATORS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 61/567,520 filed December 6, 2011 and the benefit of U.S. Provisional Patent Application No. 61/616,249 filed March 27, 2012.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the field of directional light modulation, 3D displays, emissive micro displays, 2D/3D switchable displays and 2D/3D autostereoscopic switchable displays.

2. Prior Art

In 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 spatial light modulator. In these 3D displays the light that typically comes from the directional backlight is usually processed by a directionally selective filter (such as a diffractive plate or a holographic optical plate for example) before it reaches the spatial light modulator pixels that modulate the light color and intensity while keeping its directionality

In some switchable 2D/3D displays a directional backlight is necessary to operate the display in different display modes. In a 2D display mode, a backlight with uniform illumination and large angular coverage is required to display a single image with spatial light modulators (such as liquid crystal displays (LCD)). In a 3D display mode, a backlight with uniform illumination and 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 spatial light modulator.

In both 2D and 3D modes, the light that comes from the directional backlight is usually processed by a directionally selective filter (such as diffractive plate, a holographic optical plate etc.) before it reaches the spatial light modulator pixels to expand the light beam uniformly while keeping its directionality.

Currently available directional light modulators are a combination of an illumination unit comprising multiple light sources and a directional modulation unit that directs the light emitted from the light sources to a designated direction (see Figures 1, 2 and 3). As illustrated in Figures 1, 2 and 3 which depict several variants of the prior art, an illumination unit is usually combined with an electro-mechanical movement device such as scanning mirrors or 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 and 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 Figures 1, 2 and 3 and U.S. Patent Nos. 5,986,811, 6,999,238, 7,106,519, 7,215,475, 7,369,321, 7,619,807 and 7,952,809).

In both electro-mechanically and electro-optically modulated directional light modulators there are three main drawbacks:

1. Response time: The mechanical movement or optical surface change are typically not achieved instantaneously and affect the modulator response time. In addition, the speed of these operations usually takes up some portion of the image frame time that reduces the achievable display brightness.

2. Volumetric aspects: These methods need a distance between the light source and directional modulation device to work with, which increases the total volume of the display.

3. Light loss: Coupling light on to a moving mirror creates light losses which in turn degrades the display system power efficiency and creates heat that has to be eliminated by incorporating bulky cooling methods that add more volume and increased power consumption.

In addition to being slow, bulky and optically lossy, the prior art directional backlight units 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 a spatio-optical light modulator that overcomes the drawbacks of the prior art, thus making it feasible to create 3D displays that provide practical volumetric and viewing experience. It is also an objective of this invention to introduce an extended angular coverage temporal spatio-optical light modulators that overcome the limitations of the prior art, thus making it feasible to create 3D and high resolution 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 proceed 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 figures of the accompanying drawings in which like reference numerals refer to similar elements.

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

Figure 2 illustrates a prior art directional light modulator that uses scanning mirrors.

Figure 3 illustrates a prior art prior directionally modulated 3D light modulator.

Figure 4 illustrates the spatio-optical directional light modulation aspects of the temporal spatio-optical directional light modulator.

Figure 5 is an isometric view of the directional light modulation principle of the spatio-optical directional light modulator.

Figure 6 illustrates an exemplary collimating wafer level optics design of the spatio-optical directional light modulator.

Figure 7 illustrates an exemplary design of the spatio-optical directional light modulator that uses wafer level optics exemplary design illustrated in Figure 6.

Figure 8 illustrates an exemplary embodiment of directional addressability within one of the spatial modulation pixel groups of the temporal spatio-optical directional light modulator.

Figure 9 illustrates an exemplary embodiment of directional modulation within one of the spatial modulation pixel groups of the temporal spatio-optical directional light modulator.

Figure 10 is a block diagram explaining the data processing block diagram of the spatio-optical directional light modulator.

Figure 11 illustrates an isometric view of an exemplary embodiment of a 3D/2D switchable display implemented by tiling a multiplicity of the spatio-optical directional light modulators.

Figure 12 illustrates an isometric view of the principle aspects of the temporal spatio-optical directional light modulator.

Figure 13A illustrates the angular emission expansion made possible by the temporal articulation aspects of the temporal spatio-optical directional light modulator.

Figure 13B illustrates the angular temporal articulation of the temporal spatio-optical directional light modulator.

Figure 14 illustrates the extended angular coverage cross section of the temporal spatio-optical directional light modulator.

Figure 15 illustrates isometric, side and top views of one embodiment of the temporal spatio-optical directional light modulator.

Figure 16 illustrates isometric, side and top views of another embodiment of the temporal spatio-optical directional light modulator.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

References in the following detailed description to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristics 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.

A new class of emissive micro-scale pixel array devices has been recently introduced. These devices feature high brightness, very fast light multi-color intensity and spatial modulation capabilities in a very small single device size that includes all the drive circuitry. The solid state light emitting pixels of one such a device may be either a light emitting diode (LED) or laser diode (LD) whose on-off state is controlled by the drive circuitry contained within a CMOS chip (or device) upon which an emissive micro-scale pixel array is bonded. The size of the pixels comprising the emissive array of such devices would typically be in the range of approximately 5-20 micron with the typical emissive surface area of the device being in the range of approximately 15-1 50 square millimeter. The pixels within the emissive micro-scale pixel array device are individually addressable spatially, chromatically and temporally, typically through the drive circuitry of its CMOS chip. One example of such devices are the QPI devices (see U.S. Patent Nos. 7,623,560, 7,767,479, 7,829,902, 8,049,231 , and 8,098,265, and U.S. Patent Application Publication Nos. 201 0/0066921 , 201 2/00331 13), referred to in the exemplary embodiments described below. Another example of such device is an OLED based micro-display. However it is to be understood that the QPI device is merely an example of the types of devices that may be used in embodiments of the present invention. Thus in the description to follow, references to a QPI device are to be understood to be for purposes of specificity in the embodiments disclosed, and not for any limitation of the present invention.

The present invention combines the emissive micro pixel array capabilities of the QPI device with passive wafer level optics (WLO) alone or with an articulated movement of the entire assembly to create a light modulator that can perform the functionalities of a directional light source and a diffractive plate of the prior art at the same time. 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. WLO are fabricated monolithically on the wafer from a polymer using ultra violet (UV) imprint lithography. Among primary advantages of WLO are the ability to fabricate small feature micro lens arrays (MLA) and to be able to precisely align multiple WLO micro lens array layers together and with an optoelectronics device such as a CMOS sensor or the QPI. The alignment precision that can be achieved by a typical WLO fabrication technique can be less than one micron. The combination of the individual pixel addressability of the emissive micro emitter pixel array of the QPI and the WLO micro lens array (MLA) that can be precisely aligned with respect to the micro emitter array of the QPI eliminates the need experienced in prior art for having a directionally selective filter in the system while relaxing the requirement for the narrow spectral bandwidth in the light source, reducing the system volume, complexity and cost simultaneously. In certain embodiments of the invention, directional modulation of the emitted light is achieved by the light divergence achieved by the WLO, and in other embodiments is achieved by the combination of the light divergence achieved by the WLO and the articulated movement of the entire assembly.

Referring to Figures 4 and 5, associated with each of the micro lens elements 400 comprising the 2-dimensional micro lens array MLA 220 is the group of individually addressable QPI pixels $(p_1, p_2, \ldots, p_n)$ whereby the light emitted from each of the pixels in this group of pixels would be refracted into one of the unique directions $(d_1, d_2, \ldots, d_n)$ within the numerical aperture (angular extent) of their associated micro lens element. The entire micro-pixel array of the QPI device 210 would comprise a multiplicity of QPI pixel groups $(G_1, G_2, \ldots, G_N)$, herein also referred to as pixel modulation groups, whereby each modulation group G_i would be associated with one of the 2-dimensional array MLA 220 lens elements and collectively the pixel modulation groups $(G_1, G_2,...,G_N)$ would then represents the spatial modulation array of the spatio-optical directional light modulators of this invention. With the temporal articulation illustrated in Figure 12 and the one-to-one association of the individual pixels $(p_1, p_2, \cdots, p_n)$ within each pixel group and the emitted light directions $(d_1, d_2,..., d_n)$, it becomes possible for the temporal spatio-optical directional light modulators of this invention conceptually illustrated in Figure 12 to have associated with each of its pixel groups G_i a multiplicity of temporally multiplexed directions $(d_{1i}, d_{2i},..., d_{ni})$; $i = 1,2, ...$, each being individually addressable by temporal addressing of the individual pixels $(p_1, p_2, \cdots, p_n)$ within each of the pixel groups $(G_1, G_2,...,G_N)$. The multiplicity of QPI pixel groups $(G_1, G_2,...,G_N)$ associated with the 2-dimensional array MLA 220 of Figure 12 would then represent the spatial modulation array of the temporal spatio-optical directional light modulator of this invention with the temporally multiplexed directions $(d_{1i}, d_{2i},..., d_{ni})$; $i = 1,2, ...$, representing the multiplicity of light modulation directions individually addressable through temporal addressability of the pixels $(p_1, p_2, \cdots, p_n)$ of the QPI device 210 comprising each pixel modulation group. In other words, the temporal spatio-optical directional light modulators would be able to spatially modulate light through addressability of the QPI pixel groups $(G_1, G_2,...,G_N)$ and directionally modulate the light emitted from each pixel group in the directions $(d_{1i}, d_{2i},..., d_{ni})$; $i = 1,2, ...$, through temporal addressability of the pixels $(p_1, p_2, \cdots, p_n)$ comprising each group. Therefore, the temporal spatio-optical directional light modulators illustrated in Figure 12 would be able to generate light that can be spatially and directionally modulated whereby the light emitted from each of the spatial locations that equals the emissive area of the QPI pixel groups $(G_1, G_2,...,G_N)$ is individually addressable through the addressability of the pixel groups as well as being directionally addressable through the temporal addressability of the individual pixel within each pixel group.

Figure 5 illustrates the spatial and directional modulation principles of the present invention. Figure 5 illustrates a 2-dimensional array comprising a multiplicity of QPI device pixel groups $G_1, G_2,..., G_N$ with each such pixel group associated with one micro lens of a wafer level micro lens array (MLA). With the one-to-one association of the individual pixels $p_1, p_2, \ldots, p_n$ within each group with the emitted light directions $d_1, d_2, \ldots, d_n$, it becomes possible for the light emitting device illustrated in Figure 5 to generate light that can be spatially and directionally modulated. Thus the light can be emitted from each of the spatial locations in the emissive area of the QPI device pixel groups $G_1, G_2, \ldots, G_N$ and be individually addressable through the addressability of the pixel groups as well as the directionally addressable through the addressability of the individual pixel within each pixel group. The individual pixels of the QPI device can be modulated so that each lens in the MLA can emit light to multiple directions simultaneously. Because of individual pixel control, the light amplitude, the time duration of the light emission, the specific light direction and the total number of light directions emitted from each micro lens can be individually adjusted through the individual addressability of the QPI device pixels.

It is obvious to a person skilled in the art that the directional modulation by a lens can be done on a single axis, or on two axes with the choice of lens type (i.e., lenticular lens array or two-axis lens array). However, precise alignment of the lens array with the pixelated light source and the achievability of small pixel size (in the order of few microns, or 10 microns or less) have prevented the realization of a directional light modulator that can generate the directional light modulation capabilities needed to create high definition 3D displays. In the present invention the high pixel resolution is achieved by leveraging the emissive micro pixel array of the QPI device, which can attain less than 10 micron pixel pitch, and the high precision alignment of lens array, which can be less than one micron, made possible by the wafer level optics. This allows the spatio-optical light modulator to achieve the spatial as well as directional modulation resolution sufficient to realize high definition 3D displays.

Figures 6 and 7 show an exemplary embodiment of the present invention. Referring to Figure 6 of this exemplary embodiment, the light emitted from each individual pixel within a pixel group G_i travels from the QPI device emissive surface to the exit aperture of a micro lens that comprises the three optical elements 610, 620 and 630. The light emitted from each individual pixel within a pixel group G_i, would be collimated and magnified to fill the exit aperture of the WLO micro lens array 220 and traverses at a specific direction within a $\Theta = \pm 15°$ angular divergence. In essence the WLO micro lens array 220 would map the light emitted from the individual pixels of the two dimensional pixel group G_i comprising the QPI device into individual directions within the three dimensional volume defined by $\Theta = \pm 15°$ angular divergence of the WLO micro lens array 220.

Referring to Figures 6 and 7 illustrating an exemplary embodiment, a multiplicity of the optical elements 610, 620 and 630 are fabricated to form micro lens array layers 710, 720 and 730 which would be precisely aligned relative to each other and relative to the associated arrays of the QPI device pixel groups G_1, G_2,..., G_N. The exemplary embodiment illustrated in Figure 7 also includes the QPI device 210 and its associated QPI device cover glass 760. The design of the optical elements 610, 620 and 630 would take into account the thickness and optical characteristics of the QPI device cover glass 760 in order to image the emissive surface of the QPI device cover glass 760. The exemplary embodiment of Figure 7 illustrates the full assembly of the spatio-optical directional light modulators. The typical total thickness of this exemplary embodiment of the spatio-optical directional light modulators of this invention illustrated in Figure 7 would be less than 5 millimeters. Such compactness of the directional light modulator is not possibly achievable by directional light modulation techniques of the prior art.

Figure 8 and Figure 9 illustrate the operational principles of the spatio-optical directional light modulator. Figure 8 illustrates an exemplary embodiment of one of the modulation groups G_i being comprised of a two dimensional array of (nxn) of the emissive pixels of the QPI device whereby for convenience the size of the pixel group G_i along one axis would be selected to be $n = 2^m$. Referring to Figure 8, the directional modulation addressability that can be achieved by the pixel group G_i would be accomplished through the addressability of the pixels comprising the modulation group G_i along each of its two axes x and y using m-bit words. Figure 9 illustrates the mapping of the light emitted from (nxn) pixels comprising the QPI device pixel group G_i into individual directions within the three dimensional volume defined by angular divergence $\pm\Theta$ of the associated WLO micro lens such as that of the exemplary embodiment 600. As an illustrative example, when the dimensions of the individual pixels of the QPI device are (5x5) microns and the QPI device pixel group is comprised of (nxn) = (2^8 x2^8) = (256x256) pixel array and the angular divergence of the associated WLO micro lens is $\Theta = \pm 15°$, then from each of the QPI device two dimensional modulation pixel groups G_i of size (1.28x1.28) millimeter at the QPI device emissive surface it would be possible to generate $(256)^2$ = 65,536 individually addressable directional light beams spanning the angular divergence of $\Theta = \pm 15°$ whereby the light generated in each of the 65,536 directions can be individually modulated in color and intensity as well, typically using a relatively high frequency pulse width modulation of each pixel color component, though other control techniques could be used if desired, such as proportional control.

Any desired spatial and directional modulation capabilities for the QPI device based spatio-optical directional light modulator would be possible using an array of (NxM) of the directional modulation groups G_i such as that described in the previous design example. If, for example, it is required to create a spatio-optical directional light modulator with spatial modulation resolution of N = 320 by M = 240 that provides $(256)^2$ = 65,536 directional modulation resolution, the spatio-optical directional light modulator would comprise an array of (320x240) directional modulation groups and when a QPI device with (5x5) micron pixel size is used, the total size of the spatio-optical directional light modulator would be approximately 41x31 cm. The light emitted from such a spatio-optical directional light modulator can be spatially modulated at a resolution of (320x240) and directionally modulated at a resolution of 65,536 within the angular divergence $\pm\Theta$ associate with its WLO micro lens array (for example $\Theta = \pm 15°$ for the exemplary embodiment 600) and can also be modulated in color and intensity in each direction.

The resolution of the directional modulation of the light modulators in terms of the number of individually addressable directions within the angular divergence $\pm\Theta$ of the wafer level micro lens array would be determined by selecting either the pixel pitch of the emissive micro emitter array QPI device or by selecting lens pitch of the wafer level micro lens array, or a combination of the two. It is obvious to a person skilled in the art that the lens system, such as that illustrated in Figure 6, can be designed to allow either wider or narrower angular divergence $\pm\Theta$. It is also obvious to a person skilled in the art that either a smaller or a larger number of pixels within each modulation group G_i to generate any desired directional modulation resolution.

Depending of the total pixel resolution of the QPI device used, such a spatio-optical directional light modulator can be implemented using a tiled array comprising a multiplicity of QPI devices. For example if a QPI device with (1024x1024) pixel resolution is used, then each such QPI device can be used to implement an array of (2x2) modulation groups G_i and the spatio-optical directional light modulator having (6x6) spatial light modulation resolution and 65,536 directional light modulation resolution would be implemented using a tiled array (3x3) of such QPI devices such as in the illustration of Figure 11.

The tiling of an array of QPI devices to implement the spatio-optical directional light modulator is made possible because of the compactness that can be achieved by the emissive QPI devices and the associated WLO. For example, with an implementation such as that illustrated in Figure 7, it would be possible to fabricate a QPI device/WLO assembly such as that illustrated in Figure 7 with width, height and thickness of 5.12x5.12x5 millimeters; respectively, to realize the (2x2) modulation group spatio-optical directional light modulator of the previous example. It would also be possible to implement such a QPI device/WLO assembly with its electrical interfaces being a micro ball grid array (MBGA) located at the opposite side of its emissive surface, which would allow the entire top surface of the QPI device/WLO assembly to constitute the emissive surface of the device, which in turn would make it possible to seamlessly tile multiplicity of such QPI device/WLO assemblies to implement any desired size of the spatio-optical directional light modulator. Figure 11 is an illustration of the tiling of multiplicity of the QPI device/WLO assemblies to implement an arbitrary size of the spatio-optical directional light modulators.

The principle of operation of the spatio-optical directional light modulator will be described in reference to the illustrations of Figure 8 and 9. Figure 8 illustrates the two dimensional addressability of each of the modulation groups G_i using m-bit resolution for the directional modulation. As explained earlier, light emitted from $(2^m$

x 2^m) individual pixels in an n x n array of the modulation group G_i is mapped by its associated WLO elements into 2^{2m} light directions within the angular divergence $\pm\Theta$ of the associated WLO micro lens. Using the (x,y) dimensional coordinates of the individual pixels within each of the modulation groups G_i, the angular coordinates (θ,ϕ) of the emitted light beam is given by:

$$\theta = \arctan\left[\frac{\sqrt{x^2+y^2}\times\tan(\Theta)}{0.5\times(n-1)}\right] \qquad \text{Eq. 1}$$

$$\phi = \arctan\left[\frac{y}{x}\right] \qquad \text{Eq. 2}$$

Where the angles (θ,ϕ) are spherical coordinates with the polar axis at θ=0 parallel to the z axis of the emissive surface of the modulation group G_i and m = $\log_2 n$ is the number of bits used to express the x and y pixel resolution of the of the modulation group G_i.

The spatial resolution of the spatio-optical directional light modulator is simply defined by the coordinates of each of the individual modulation group G_i within the two dimensional array of modulation groups comprising the overall spatio-optical directional light modulator. There is of course, some cross talk between pixels of one group and the micro lens for an adjacent group. However the cross talk is substantially reduced by the following design aspects. First, because of the inherently collimated light emission of the QPI device, the light emitted from the QPI device pixels is typically confined to a ±17° cone for the case when the QPI device pixels are light emitting diode or to a ±5° cone for the case when the QPI device pixels are laser diodes . Thus placing the wafer level optics (WLO) collimation lens elements close to the cover glass 660 of the QPI device as illustrated in Figure 6 will make most of the light emitted from each modulation group edge pixels be confined to its associated WLO lens elements 600. Second, as an added measure, a few (some) edge pixels of each pixel group are turned off to further avoid leakage of light (cross-talk) between adjacent lenses of the WLO micro lens array. For example, given the ±17 confined emission of the QPI device with its pixel are light emitting diodes and the close placement of the first micro lens element as illustrated in Figure 6, simulation shows that a dark ring around the outer edge of the modulation group comprising as few as only 5 pixels will reduce the cross-talk to below 1%. When the QPI device pixels are laser diodes, the required number of turned off pixels will be even less and may be not even required since in this case the QPI device pixel light emission is confined to an even much narrower ±5° cone. The end result may be some (a few) inactive, blank or dead pixel positions between active pixels in the QPI devices in the array. Of course baffles and/or band-limiting light diffusers could be used if desired, though they tend to complicate the design of the light modulator and cause excessive loss of light.

Figure 10 illustrates an exemplary embodiment of the data processing block diagram of the spatio-optical directional light modulators of this invention. The input data to the spatio-optical directional light modulator will be formatted in multiple bit words whereby each input word contains the three data fields; one field being the address of modulation group G_i within the modulation group array comprising the spatio-optical directional light modulator while the remaining two data fields provide the data representation of the light to be emitted from that modulation group in terms of its color, intensity and direction. Referring to Figure 10, the data processing block 120 decodes the modulation group address field of the input data and route the light modulation data fields to the QPI device associated with the designated modulation group. The data processing block 130 decodes the routed modulation group address field and maps it to the address of the designated modulation group. The data processing block 140 decodes the directional modulation data field and maps it into the address of designated pixel address within the modulation group. The data processing block 150 concatenates the resultant pixel address with the associated light intensity and color data fields of the input data. The data processing block 160 decodes the designated pixel address and routes the light modulation data to the designated pixel within the designated QPI device comprising the spatio-optical directional light modulator.

In using 16-bit for representing the directional modulation and the typical 24-bit for representing the modulated light intensity and color in each direction, the total number bits that would represent the modulation data word for each modulation group would be 40-bit. In assuming, without loss of generality, that such 40-bit words would be inputted to the spatio-optical directional light modulators for addressing its constituent modulation groups sequentially; i.e., sequential addressing is used to input the modulation group data 40-bit words, block 120 of Figure 10 would be responsible for routing the sequentially inputted data word to the designated QPI device. Block 130 of Figure 10 would be responsible for routing the modulation data to the designated modulation group. Block 140 of Figure 10 would be responsible for mapping the 16-bit directional modulation data field into the designated address of the pixel with the designated modulation group. Block 150 of Figure 10 would be responsible for concatenating the 24-bit light intensity and color data with the mapped pixel group address. Block 160 of Figure 10 would be responsible for routing the 24-bit light intensity and color modulation data to the designated pixel within the designated QPI device comprising the spatio-optical directional light modulator. With this exemplary data processing flow of the 40-bit word sequential data input, the spatio-optical directional light modulators would modulate the light emitted from its aperture in intensity, color and direction based on the information encoded within its input data. The light intensity and color modulation may be, by way of example, pulse width modulation of the on/off times of the multi color pixels to control the average intensity of the light and to control the intensity of each color component making up the resulting color, though other control techniques may be used if desired. In any event, the direction and intensity are controlled, and color, direction and intensity are controlled in a multi color system.

Possible Applications Include

The spatio-optical directional light modulators of this invention can be used as a backlight for liquid crystal display (LCD) to implement a 3D display. The spatio-optical directional light modulator by itself can be used to implement a 3D display of an arbitrary size that is realized, for example, as a tiled array of multiplicity of QPI devices/WLO assemblies such as that illustrated in Figure 11. The light modulators can also be operated as a 2D high resolution display. In this case the individual pixels of the QPI device would be used to modulate the color and intensity while its integrated WLO would be used to fill the viewing angle of the display It is also possible for the light modulators to be switched from 2D to 3D display modes by adapting the format of its input data to be commensurate with the desired operational mode. When the light modulators are used as a 2D display, its light angular divergence will be that associated with its WLO micro lens array $\pm\Theta$ and the pixel resolution of the individual modulation group G_i will be leveraged to achieve higher spatial resolution.

Figure 12 conceptually illustrates another embodiment, a temporal spatio-optical directional light modulator. As illustrated in Figure 12, the directional light modulators are comprised of an emissive micro array QPI device 210 with a WLO micro lens array (MLA) 220 mounted directly on top of its emissive surface with the entire assembly being temporally articulated around at least one axis, and preferably around both its **x** and **y** axes by angles within the range of $\pm a_x$ and $\pm a_y$; respectively. The articulation of the QPI/ MLA assembly 230 as illustrated in Figure 12 would be accomplished by placing the entire assembly on a 2-axis gimbal whereby the **x**-axis of the gimbal is temporally actuated by an angle within the range of $\pm a_x$ and the **y**-axis of the gimbal is temporally actuated by an angle within the range of $\pm a_y$. The **x**-axis and **y**-axis temporal articulation provided by the 2-axis gimbal will cause the directional modulation angle of the light emitted from QPI/MLA assembly 230 to be temporally extended by $2a_x$ around the **x** direction and by $2a_y$ around the **y** direction beyond the angular extent provided by the micro lens elements of the MLA 220 (see Figure 4). As used herein, the words gimbal and two axis gimbal are used in the general sense, and mean any structure that will allow rotation, at least through a limited angle, about either or both any two orthogonal axes at any time. Thus concentric rings, ball joints and any other structure that will provide that capability are included within the definition.

The **x**-axis and **y**-axis articulation of QPI/MLA assembly 230 as illustrated in Figure 12 will cause the light emitted in the directions $(d_1, d_2, \ldots, d_n)$ to be temporally multiplexed into the multiplicity of light directions $(d_{1i}, d_{2i}, \ldots, d_{ni})$; $i = 1,2, \ldots$, which extend over the angular extent provided by the lens elements of the MLA 220 plus $2\alpha_x$ in the **x** direction and by $2\alpha_y$ in the **y** directions. This is illustrated in Figure 13A which shows the temporal expansion of the QPI/MLA assembly 230 angular emission extent along one articulation axis, for the purpose of illustration. Referring to Figure 13A, the angle Θ represents the angular extent of one lens element of the MLA 220 and the angle α represents the composite instantaneous articulation angle of the lens element as a result of the gimbal articulation by the angles $a_x(t)$ and $a_y(t)$ around the x-axis and the y-axis; respectively. The articulation of QPI/MLA assembly 230 as illustrated in Figure 12 and explained by Figure 13A enable the pixels within emissive micro-scale array of the QPI device 210, which are individually addressable through the QPI drive circuitry, to emit light that is modulated both spatially, chromatically and directionally whereby the angular extent of the directionally modulated light is temporally expanded by an angle $2a_x$ in the x direction and by an angle $2a_y$ in the y direction beyond the angular extent Θ (or numerical aperture) of the lens elements of the MLA 220. Furthermore, temporal articulation of the temporal spatio-optical directional light modulator 200 would temporally increase the modulated number of light directions $(d_1, d_2,..., d_n)$ by the ratio of the angular extent expansion in each articulation direction expressed as $(\Theta + \alpha_x)(\theta + \alpha_\gamma)/\Theta^2$.

The 2-axis articulation of the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators 200 can be in either temporally continuous or discrete (stepwise). Figure 13B illustrates the composite temporal articulation angle $a\{t)$ of the QPI/MLA assembly 230 in one axis, for the purpose of illustration, when the articulation is temporally continuous 1310 and when the actuation is temporally discrete 1320. When the temporal articulation of the temporal spatio-optical directional light modulator 200 is discrete or stepwise (1320), the typical angular step size would preferably be proportional to the ratio of the angular extent Θ of the MLA 220 to spatial resolution the QPI/MLA assembly 230. As illustrated in Figures 13A and 13B, the temporal articulation of the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators would typically be a repetitive (or periodic) and independent around each of the 2-axis. The repetition periods of the articulation of the temporal spatio-optical light modulators would typically be proportional to and synchronized with display input data frame duration (for the purpose of reference, the image input data to a typical display arrives at 60 frames per second and is often referred to as 60Hz frame rate input). The maximum values $\pm\alpha_{xmax}$ of the temporal articulation illustrated in Figures 13A and 13B would determine the expanded angular extent provided by the temporal spatio-optical light modulator which is determined by the value $\pm(\Theta + \alpha_{max})$, where the angle Θ represents the angular extent of the lens elements of the MLA 220. The periodicity of the x-axis and y-axis articulation collectively would typically be selected to enable temporal coverage of the desired expanded angular extent of the temporal spatio-optical directional light modulators 200 within a required display input frame rate.

Figures 12, 13 and 14 illustrate the angular coverage cross section 510 of the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators 200 being comprised of a multiplicity of the temporally angular coverage cross section 520 of the MLA lens element. Appropriately selected temporal articulation $a_x(t)$ and $a_y(t)$ of the QPI/MLA assembly 230 around its x-axis and y-axis; respectively, will generate the angular coverage that is comprised of multiplicity of temporally multiplexed angular coverage of the MLA 220 lens element. Depending on the magnitude of the angular articulation a_x and a_y of the QPI/MLA assembly 230 around their x and y axes, the shape of the angular coverage cross section can be tailored in aspect ratio. The articulation rate around the x and y directions would be sufficient to ensure that the temporally generated light directions within the angular coverage have adequate duty cycle (modulation duration) within the modulation frame of the input image data. For example, when the modulation frame of the input image data is 60 image frames per second, which is typically referred to as 60 Hz image frame rate, each of the light directions within each of the temporal angular coverage illustrated in Figure 14 will need to be modulated once per frame, thus making the articulation rate required to generate angular coverage illustrated in Figure 14 to be at least 180 Hz around either the x or the y axis. In other words, for the angular coverage example illustrated in Figure 14 where the size of the temporal angular coverage is three times the size of angular coverage in each axis, the articulation rate around either the x or the y directions for the illustration of Figure 14 would need to be at least three times the input image data frame rate. The angular coverage of the MLA lens element can be either overlapping or non-overlapping. In general the articulation rate of the QPI/MLA assembly 230 around either the x or y axis will have to be at least equal to the modulation frame rate of the input image data multiplied by a factor that equals to ratio of the size (in degrees) of the angular coverage long each axis to the size (in degrees) of the angular coverage along the same axis.

Referring to Figure 14, with the temporal articulation of the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators 200 having the angular coverage and comprising the multiplicity of the directionally modulated light emitted corresponding with the multiplicity of pixels comprising the QPI device 210, a new set of directionally modulated light beams would be continuously added as some drop off temporally in a pipeline fashion until the expanded angular extent of the temporal spatio-optical directional light modulators 200 are fully covered. At any given instant the full emissive aperture of the QPI/MLA assembly 230 would be utilized to accumulate (modulate) the desired intensity of the light beam (typically by pulse width modulation, though proportional control could be used if desired) at any given direction as that direction remains temporally within the coverage of the articulated aperture. As a result of this temporal spatio-optical pipelining of the multiplicity of the directionally modulated light beams, the response time of the temporal spatio-optical light modulators can be made to be commensurate with the image data input rate with minimal latency. The time duration a given direction remains within the angular coverage would determine the modulation time available for modulating the light intensity in that direction, and as a result, unless compensated, the directions within the peripheral area of the expanded angular coverage could have less intensity than the interior region of the angular coverage. This intensity edge tapering effect would be somewhat similar to the Fresnel losses typically encountered at the edge of an optical system except in the case of the temporal spatio-optical light modulators, such an effect can be compensated by appropriate selection of the rate of the temporal articulation of the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulator 200.

As an alternative, using the 3X3 example again, if Θ_x represents the angular extent (half angle) of one lens element around the x axis and Θ_y represents the angular extent of one lens element around the y axis and if a_x equals $2\Theta_x$ and a_y equals $2\Theta_y$, the total angular extent, including the articulation, will be three times the angular extent of one micro lens element (3 times $2\Theta_X$ or 3 times $2 0_y$). By way of example, for the x axis, these three contiguous angular extents will be:

$(-\alpha_x-\theta_x)$ to (-<¾)

(-<¾) to (<¾), and

(θ_x) to (ι¾+α_x)

each angular extent also being constituting an angular increment in articulation.

The three contiguous individual angular extents in each direction can be considered as a two dimensional angular extent matrix as follows:

1, 2, 3

4, 5, 6

7, 8, 9

This alternative is a discrete technique, namely to display angular extent 1 for an allotted time, then advance around a first axis by one angular increment and then display angular extent 2 for the same allotted time, then advance one more angular increment and display angular extent 3 for the allotted time, then advance one angular increment on the other axis to display extent 6 for the allotted time, then go back one angular increment on that axis and display angular extent 5 for the allotted time, etc. After angular extent 9 is displayed for the allotted time, one could repeat 9 (continue displaying for twice the allotted time and then backtrack to avoid more than one angular increment in one axis at a time, though this would be expected to create a flicker unless a higher rate was used. A better approach would be to go from angular extent 9 to angular extent 1, a jump of two angular increments on 2 axes at the same time. However a jump of two angular increments on 2 axes should not take twice as long as an angular change of one angular increment on one axis, as the x and y axes will be independent of each other, and any change comprises an angular acceleration followed by an angular deceleration, so the average velocity is higher for a change of two angular increments than for a change of one angular increment. Still further alternatives might include a combination of discrete and continuous techniques. The point is that there are many alternatives one could choose from, all of which are within the scope of the present invention.

One embodiment of this invention, herein referred to as 1500, is illustrated in Figure 15, which includes isometric, top view and side view illustrations of this embodiment. As illustrated in Figure 15, the temporal spatio-optical directional light modulators are realized by bonding the QPI/MLA assembly 230 (depicted in Figure 12) on the topside of the 2-axis gimbal assembly 1520 which is fabricated using multiple silicon substrate layers; namely, a hinge layer 1521 , a spacer layer 1528 and a base layer 1530 . As illustrated in Figure 15, the hinge layer 1521 of the 2-axis gimbal assembly 1520 is comprised of an outer frame 1522, an inner ring 1523 and the inner segment 1525 upon which QPI/MLA assembly 230 would be bonded (1525 is hereinafter also referred to synonymously as the device bonding pad 1525). The gaps between the outer frame 1522, the inner ring 1523 and the inner segment 1525 would be etched using standard semiconductor lithography techniques. The inner segment 1525 is physically connected along the x-axis to the inner ring 1523 by two silicon hinges 1524, each typically approximately in the range of 0.3-0.5 mm wide, which would act as the x-axis hinge and would also to define the neutral x-axis position of the gimbal and act as a mechanical resistance spring for the x-axis articulation. The inner ring 1523 is connected along the y-axis to the outer frame 1522 by two the silicon hinges 1526, each typically approximately in the range of 0.3-0.5 mm wide, which would act as the y-axis hinge and would also define the neutral y-axis position of the gimbal and act as a mechanical resistance spring for the y-axis articulation. The two pairs of silicon hinges 1524 and 1526 constitute the pivot points of the 2-axis gimbal around which the x and y articulation would be performed. The inner segment 1525 of the hinge layer 1521 of the 2-axis gimbal assembly 1520 contains multiplicity of contact pads to which the QPI/MLA assembly 230 will be bonded using standard soldering techniques such as flip chip solder balls, thus making the inner segment 1525 become the bonding pad upon which QPI/MLA assembly 230 would be bonded. Embedded within the inner segment 1525 of the hinge layer 1521 of the 2-axis gimbal assembly 1520 are multiplicity of metal rails which connect a set of contact pads on the topside of the inner segment 1525 to a set of device contact pads 1527 placed along the periphery of the outer frame 1522 via the x-axis and y-axis silicon hinges 1524 and 1526. The set of contact pads on the topside of the inner segment

1525 are the contact pads that would provide electrical and physical contact to the backside of the QPI/MLA assembly 230.

Referring to the side view illustration of Figure 15, the QPI/MLA assembly 230 is shown bonded to the topside of the inner segment 1525. As explained earlier, this would be both an electrical and physical contact bonding between the contact pads on the topside of the inner segment 1525 and the contact pad at the backside of the QPI/MLA assembly 230 using solder or eutectic ball grid array type bonding. Also illustrated in Figure 15 side view is the spacer layer 1528 which would be bonded at wafer level with the base layer 1530 topside and with the hinge layer backside using BenzoCycloButene (BCB) polymer adhesive bonding or the like. The height (or thickness) of the spacer layer 1528 would be selected to accommodate the vertical displacement of the corner of the inner segment 1525 together with the bonded QPI/MLA assembly 230 at the maximum actuation angle. For example, if the diagonal of the inner segment 1525 together measures 5 mm and the maximum articulation angle at the corner is 15°, then the thickness of the spacer layer 1528 should measure approximately 0.65 mm in order accommodate the vertical displacement of the corner of the inner segment 1525 at the maximum articulation.

Referring to the side view illustration of Figure 15, the articulation of the inner segment 1525 together with the bonded QPI/MLA assembly 230 would be accomplished using a set of electromagnets 1535 placed at the four corners of the backside of the inner segment 1525, and a set of permanent magnets 1536 placed on the topside of base layer 1530 in alignment with the four corners of the backside of the inner segment 1525. The electromagnets 1535 would be a coil having a metal core formed at wafer level using multilayer imprint lithography on the backside of the inner segment 1525. The permanent magnets 1536 would be a thin magnetic strip typically of neodymium magnet (Nd_2Fei_4B) or the like. Articulation of the inner segment 1525 together with the bonded QPI/MLA assembly 230 as described earlier would be accomplished by driving the set of electromagnets 1535 with an electrical signal having the appropriate temporal amplitude variation to affect the appropriate temporal variation in the magnetic attraction between the set of electromagnets 1535 and permanent magnets 1536 that would cause of the inner segment 1525 together with the bonded QPI/MLA assembly 230 to be temporally articulated as described earlier. The drive electrical signals to the set of electromagnets 1535, which are generated by the QPI device 210 and supplied to the set of electromagnets 1535 via the metal rails and contacts incorporated in the inner segment 1525 described earlier, would be made synchronous with the pixel modulation performed by the QPI device 210 to the extent that will enable the desired directional modulation of the intensity and color modulated light emitted from the pixel array of the QPI device 210. The temporal variation of the drive electrical signals to the set of electromagnets 1535 would be selected to enable the temporal angular articulation of the inner segment 1525 together with the bonded QPI/MLA assembly 230 around both of their x-axis and y-axis as illustrated in Figure 15. Depending on the thickness of the silicon substrate of the hinge layer 1521 and the selected width of the silicon hinges 1524 and 1526, the maximum value $\pm\alpha_{max}$ of the temporal angular articulation *a(t)* illustrated in Figure 13B that can be achieved by embodiment 1500 of this invention would typically be in the range from ±15° to ±17°.

The drive electrical signals to the set of electromagnets 1535, which are generated by the QPI device 210 and supplied to the set of electromagnets 1535 via the metal rails and contacts incorporated in the inner segment 1525 described earlier, would be comprised of a base component and a correction component. The base component of the drive electrical signals to the set of electromagnets 1535 would represent a nominal value and a correction component would be derived from an angular articulation error value generated by a set of four sensors positioned on the backside of the inner segment 1525 in alignment with the silicon hinges 1524 and 1526. These sensors would be an array of infrared (IR) detectors placed on the backside of the inner segment 1525 in alignment with four IR emitters placed on the topside of the base layer 1530. The output values these four IR detector arrays will be routed to the QPI device, again via the metal rails and contacts incorporated in the inner segment 1525 described earlier, and used to compute an estimate of the error between the derived and the actual articulation angle which will be incorporated as a correction to the drive signals provided by the QPI to the set of electromagnets 1535. The sensors positioned on the backside of the inner segment 1525 could also be micro-scale gyros properly aligned to detect the actuation angle along each of the 2-axis of the gimbal.

Another embodiment of this invention is illustrated in Figure 16, herein referred to as 1600. Figure 16 includes isometric views and side view illustrations of this embodiment. As illustrated in Figure 16, the embodiment 1600 of this invention is comprised of the 2-axis gimbal assembly 1620 with the QPI/MLA assembly 230 bonded on top of it. Figure 16 also shows an exploded isometric illustration of the embodiment 1600 that shows the constituent layers of the 2-axis gimbal assembly 1620 of this embodiment. As illustrated in Figure 16, the temporal spatio-optical directional light modulators are realized by bonding the QPI/MLA assembly 230 (depicted in Figure 12) on the topside of the 2-axis gimbal assembly 1620 which is fabricated using multiple silicon substrate layers; namely, a pad layer 1621 , a spring layer 1625 and a base layer 1630. The topside of the pad layer 1621 incorporates a multiplicity of contact pads to which the QPI/MLA assembly 230 is to be bonded using standard soldering techniques such as flip chip solder balls, thus making the topside of the pad layer 1621 being the bonding layer/contact pad 1623 upon which QPI/MLA assembly 230 would be bonded. The backside of the pad layer 1621 incorporates the spherical pivot 1635 which would be formed by embossing polycarbonate polymer on the backside of the pad layer 1621 at the wafer level using UV imprint lithography or the like. The pad layer 1621 together with the spherical pivot 1635 embossed on its backside will be referred to as hinged pad 1621/1 635. The elevation of the center of the spherical pivot 1635 determines the elevation of the x and y axes of the angular deflection. The topside of the base layer 1630 incorporates the spherical socket 1636 which would be formed by embossing of polycarbonate polymer on the topside of the base layer 1630 at the wafer. The base layer 1630 together with the spherical socket 1636 embossed on its topside will be referred to as the pedestal 1630/1 636. The surface curvature the spherical pivot 1635 incorporated on the backside of the pad layer 1621 and the spherical socket 1636 incorporated on the topside of the base layer 1630 will be ±matched in order to allow the hinged pad 1621/1 635 to make it a 2-axis articulated pad when placed on top of the pedestal 1630/1 636. Although the embossed surfaces of the spherical pivot 1635 and spherical socket 1636 will be of optical quality in terms of surface roughness in the order of a few nm RMS, possible friction between the two surfaces due to the articulation movement would be reduced by coating the surfaces of the spherical pivot 1635 and spherical socket 1636 with a thin layer (50-1 00 nm) of graphite.

The hinged pad 1621/1 635 is retained in place within the surface curvature of the pedestal 1630/1 636 by the spring layer 1625 which contains at each of its four corners a single spiral shaped spring 1626 that is etched into the spring layer 1625. As illustrated in Figure 16 exploded view isometric, the inner end of each of the four spiral shaped springs incorporates an inner bonding pad 1627 which corresponds to an identical contact pad 1622 located at the backside of the pad layer 1621 . Embedded within the spiral shaped springs 1626 are multiple metal rails that are used to route the electrical interface signals from its inner bonding pad 1627 to a set of edge contacts/pads 1628 located at the peripheral edge of the backside of the spring layer 1625. The edge contacts/pads 1628 on the backside of the outer end of the spring layer 1625 correspond to a matching set of bonding pads 1629 that are located at the peripheral edge of the base layer 1630. The edge contacts on the topside of the base layer 1630 are connected via metal rails embedded within the base layer to a set of device contact pads 1631 that are located on the backside of the base layer 1630. In the final assembly of the embodiment 1600 of this invention, illustrated in the side view of Figure 16, the four spiral shaped springs 1626 will be expanded when the backside of the edge contacts/pads 1628 of the spring layer 1625 is bonded to the topside bonding pad 1629 of the base layer 1630 and the inner bonding pad 1627 of the spiral shaped spring 1626 is bonded the corresponding contact pad 1622 on the backside of the pad layer 1621 . When the spring layer 1625 is bonded to the backside of the pad layer 1621 and to the topside of the base layer 1630 spiral shaped springs 1626 as just explained, the four spiral springs become fully expanded and in that full expanded configuration they serve the multiple purposes of: (1) creating a spring load resistance needed to retain the spherical pivot 1635 within the spherical socket 1636; (2) creating the mechanical balance needed for sustaining the neutral position of the hinged pad 1621/1 635; and (3) routing the electrical interface signals from the device contact pads 1631 to the bonding layer/contact pad 1623 of the

QPI/MLA assembly 230. Referring to the side view illustration of Figure 16, the QPI/MLA assembly 230 is shown bonded to the topside bonding layer/contact pad 1623 of the pad layer 1621. This would be both an electrical and physical contact bonding between the bonding layers/contact pads 1623 and the contact pad at the backside of the QPI/MLA assembly 230 using solder or eutectic ball grid array type bonding. In the operational configuration the full device assembly 1600 would be bonded using the contact pad 1631 located on the backside of the base layer to a substrate or printed circuit board using solder or eutectic ball grid array type bonding.

Also illustrated in Figure 16 side view is the extended height of the spherical socket 1636 which would be selected to accommodate the vertical displacement of the corner of the hinged pad 1621/1 635 together with the bonded QPI/MLA assembly 230 at the maximum actuation angle. For example, if the diagonal of the hinged pad 1621/1 635 together with the bonded QPI/MLA assembly 230 measures 5 mm and the maximum actuation angle at the corner is ±30°, then the thickness of the extended height of the spherical socket 1636 should measure approximately 1.25 mm in order accommodate the vertical displacement of the corner of the of the hinged pad 1621/1 635 together with the bonded QPI/MLA assembly 230 at the maximum actuation angle.

The actuation of the pad layer 1621 together with the bonded QPI/MLA assembly 230 would be accomplished using a set of electromagnets embedded within the spherical pivot 1635 and a set of permanent magnets embedded within the spherical socket 1636. The actuation electrical drive signal would be routed to electromagnets embedded within the spherical pivot 1635 in order to affect the actuation movement described in the earlier paragraphs. The base component of the actuation electrical drive signals to the electromagnets embedded within the spherical pivot 1635 would represent a nominal value and a correction component that would be derived from an angular articulation error value generated by a set of four sensors positioned on the backside of the pad layer 1621. These sensors are an array of infrared (IR) detectors placed on the backside of the pad layer 1621 in alignment with four IR emitters placed on the topside of the base layer 1630. The output values these four IR detector arrays will be routed to the QPI device, again via the metal rails and contacts incorporated in the pad layer 1621 described earlier, and used to compute an estimate of the error between the derived and the actual articulation angle which will be incorporated as a correction to the drive signals provided by the QPI device to the set of electromagnets embedded within the spherical pivot 1635. The sensors positioned on the backside of the pad layer 1621 could also be micro-scale gyros properly aligned to detect the actuation angle along each of the 2-axis of the gimbal.

The permanent magnets embedded within the spherical socket 1636 would be a thin magnetic rods or wires, typically of neodymium magnet (Nd_2Fei_4B) or the like, and would be shaped to provide a uniform magnetic field across the curved cavity of the spherical socket 1636. Actuation of the pad layer 1621 together with the bonded QPI/MLA assembly 230 as described earlier would be accomplished by driving the set of electromagnets embedded within the spherical pivot 1635 with an electrical signal having the appropriate temporal amplitude variation to affect the appropriate temporal variation in the magnetic attraction between the set of electromagnets embedded within the spherical pivot 1635 and permanent magnets embedded within the spherical socket 1636 that would cause of the pad layer 1621 together with the bonded QPI/MLA assembly 230 to be temporally articulated as described earlier. The drive electrical signals to the set of the set of electromagnets embedded within the spherical pivot 1635, which are generated by the QPI device and routed via the metal rails and contacts incorporated on the pad layer 1621 described earlier, would be made synchronous with the pixel modulation performed by the QPI device to an extent that will enable the desired directional modulation of the intensity and color modulated light emitted from the pixel array of the QPI device. The temporal variation of the drive electrical signals to the set of electromagnets embedded within the spherical pivot 1635 would be selected to enable the temporal angular articulation of the pad layer 1621 together with the bonded QPI/MLA assembly 230 along both of their x-axis and y-axis as illustrated in Figure 15. Depending on the extended height of the spherical socket 1636 which governs the maximum vertical displacement of the corner of the pad layer 1621 together with the bonded QPI/MLA assembly 230, the maximum value $\pm\alpha_{max}$ of the temporal angular articulation $a(t)$ illustrated in Figure 15 that can be achieved by the embodiment 1600 of this invention would typically be in the range from ±30° to ±35°.

A person skilled in the art would know that the gimbal actuators of the embodiments 1500 and 1600 of this invention described in the previous paragraphs can be implemented to achieve substantially the same objective by exchanging the positions of the electromagnets and the permanent magnets.

The two exemplary embodiments 1500 and 1600 of this invention differ mainly in the maximum value α_{max} of the temporal angular articulation *a(t)* each can achieve and in the outer area each embodiment needs beyond the boundary of the QPI/MLA assembly 230. First, as illustrated in Figure 16, in the embodiment 1600 of this invention the 2-axis gimbal is fully accommodated within the footprint area of the QPI/MLA assembly 230 (hereinafter refer to a zero-edge feature) while as illustrated in Figure 15 in the embodiment 1500 of this invention the 2-axis gimbal is accommodated at the outer periphery of the QPI/MLA assembly 230 outer boundary. Second, the maximum value a_{max} of the temporal angular articulation *a(t)* embodiment 1600 can achieve could possibly be twice as large as what could be provided embodiment 1500. Of course the larger maximum value a_{max} of the temporal angular articulation *a(t)* that can be accomplished by the embodiment 1600 comes at the expense of requiring larger vertical height than the embodiment 1500. The zero-edge feature of the embodiment 1600 makes it more suitable for being tiled to create a large area display while the low profile (low height) feature of the embodiment 1500 makes it more suitable for creating compact displays for mobile applications.

The angular extent Θ of the MLA 220 micro lens system 610, 620 and 630 can be made either larger or smaller than the ±15° of the exemplary embodiment of Figure 6 through appropriate design selection of the refracting surfaces of the micro lens system 610, 620 and 630 or by increasing or decreasing the number of its optical elements. It should be noted, however, that for a given resolution in terms of number of pixels within the pixel modulation group G_i, changing the angular extent Θ of the MLA 220 micro lens system would result in a change in the angular resolution (separation) between the directionally modulated light beams emitted by the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators of this invention. For example with the $\Theta = \pm 15°$ angular extent of the previous exemplary embodiment, if the pixel group G_i comprises (128x128) pixels, then the angular resolution between the directionally modulated light beam emitted by the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators of this invention would be approximately $\delta\Theta = 0.23°$. This same angular resolution value of $\delta\Theta = 0.23°$ can also be achieved by reducing the angular extent of the MLA 220 micro lens system to $\Theta = \pm 7.5°$ and the number of pixels comprising the pixel group G_i to (64x64) pixels. In general using a higher F/# (i.e., smaller value of the angular extent Θ) for the MLA 220 micro lens system would allow achieving a given angular resolution value using a smaller pixel modulation group G_i size, which in turn would result in the availability of more pixels within a given pixel resolution of the QPI device 210 to create more of the pixel groups G_i and consequently higher spatial resolution than can be achieved by the QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators of this invention. This deign tradeoff would allow selecting the appropriate balance between the F/# of the MLA 220 micro lens system design parameters and spatial resolution that can be achieved by the QPI/MLA assembly 230. On the other hand, when the F/# of the MLA 220 micro lens system is increased to increase the spatial resolution, the angular extent that can be achieved by the QPI/MLA 230 of the temporal spatio-optical directional light modulators of this invention would be reduced. At this point the maximum value α_{max} of the temporal angular articulation $a(t)$ will become a part of the design tradeoff to recover the angular extent lost in favor of increasing the spatial resolution. In the previous example when the maximum value a_{max} of the articulation angle is selected to be $a_{max} = \pm 7.5°$, the temporal spatio-optical directional modulators of will be able to achieve a expanded angular extent of $(\alpha_{max} + \Theta) = \pm 15°$ using the pixel group G_i of (64x64) pixels. In essence for a given angular resolution value of $\delta\Theta$, the maximum value of the articulation angle a_{max} comes into the tradeoff as a parameter that can be used either to increase the angular extent of the directional modulation or the spatial resolution that can be achieved by the temporal spatio-optical directional modulators.

It should be noted that unlike prior art that uses a scanning mirror to tempo-directionally modulate a light beam, the temporal spatio-optical light modulators of this invention differ in one very important aspect in that it generates, at any given instance of time, a multiplicity of light beams that are directionally modulated simultaneously. In the case of the temporal spatio-optical light modulators of this invention, the multiplicity of directionally modulated light beams would be temporally multiplexed by the articulation of the gimbaled QPI/MLA assembly 230 to expand the directional modulation resolution and angular extent. As explained earlier (see Figure 14), as the gimbaled QPI/MLA assembly 230 is articulated a new set of directionally modulated light beams are added as some drop off temporally in a pipeline fashion until the expanded angular extent provided by the temporal spatio-optical light modulators of this invention is fully covered. Accordingly, at any given instant the full emissive aperture of the gimbaled QPI/MLA assembly 230 is utilized to accumulate the desired intensity at any given direction as that direction remains temporally within the coverage of the articulated aperture of QPI/MLA assembly 230. As a result of this temporal pipelining of the multiplicity of the directionally modulated light beams, the response time the temporal spatio-optical light modulators of this invention can be made to be commensurate with the image data input rate with minimal latency. In addition, the articulation of the gimbaled QPI/MLA assembly 230 of the temporal spatio-optical directional light modulators of this invention can be made in a non-stop pattern that would result in minimal or no blanking of the emissive aperture of the gimbaled QPI/MLA assembly 230 as it is articulated across the expanded angular extent of the temporal spatio-optical light modulators of this invention. Thus, the slow response time, poor efficiency and large volume drawbacks of prior art directional light modulators are all substantially overcome by the temporal spatio-optical light modulators of this invention.

Figure 8 and Figure 9 illustrate the operational principles of the temporal spatio-optical directional light modulators. Figure 8 illustrates an exemplary embodiment of one of the pixel groups G_i being comprised of a two dimensional array of (nxn) of the emissive pixels of the QPI device 210 whereby for convenience the size of the pixel group G_i along one axis would be selected to be $n = 2^m$. Referring to Figure 8, the directional modulation addressability that can be achieved by the pixel group G_i would be accomplished through the addressability of the (nxn) pixels comprising the modulation group G_i along each of its two axes x and y using m-bit words. Figure 9 illustrates the mapping of the light emitted from (nxn) pixels comprising the QPI pixel modulation group G_i into individual directions within the three dimensional volume defined by angular extent 0 of the associated MLA 220 micro lens element such as that of the exemplary embodiment illustrated in Figure 6. As an illustrative example, when the dimensions of the individual pixels of the QPI are (5x5) microns and the QPI pixel group G_i is comprised of (nxn) = (2^7 x2^7) = (128x128) pixel array and the angular extent of the associated MLA 220 micro lens element is 0 = ±15°, then from each of the QPI two dimensional modulation pixel groups G_i of size (0.64x0.64) millimeter at the QPI emissive surface it would be possible to generate $(128)^2$ = 16,384 individually addressable directional light beams spanning the angular extent of 0 = ±15° whereby the light generated in each of the 16,384 directions can be individually modulated in color and intensity as well. When the QPI/MLA assembly 230 is articulated as described earlier (see Figure 12 and Figure 13A) using the 2-axis gimbals of the embodiments 1500 and 1600, the directional modulation angular extent provided by the lens elements of the QPI/MLA assembly 230 will be temporally extended by the maximum articulation angle $\pm\alpha_{max}$ provided by the gimbal. Thus the directional modulation angular extent provided by the temporal spatio-optical directional light modulators of this invention would be temporally extend over an angular coverage totaling $\pm(0 + \alpha_{max})$. For example when the angular extent of the MLA 220 lens element is 0 = ±15°, and the maximum articulation angle a_{max} = ±30°, then the expanded angular extent that would provided by the temporal spatio-optical directional light modulators would be $(\Theta + \alpha_{max})$ = ±45°, and the light modulation directions it would able to temporally generate would be $[n(0 + \alpha_{max})/0]^2$ = 9x the number of light modulation directions that can be generated by the QPI/MLA assembly 230 (see Figure 14); namely, $9(128)^2$ = 147,456 light modulation directions. Meaning that the number of light modulation directions that can be generated by the temporal spatio-optical directional light modulators of this invention would be (3nx3n), where (nxn) is the size, in terms of number of QPI pixels, of the pixel groups G_i associated with one of the MLA 220 lens elements. Thus, for this example the temporal spatio-optical directional light modulator would offer an expanded directional modulation resolution to 9x the directional modulation resolution provided by QPI/MLA assembly 230. In general, the directional modulation resolution provided by the temporal spatio-optical directional light modulators would $[n(\Theta + \alpha_{max})/0]^{2}$ within an angular extent that extends over an angle of $\pm(\Theta + \alpha_{max})$.

In addition to the directional modulation capabilities for the temporal spatio-optical directional light modulators of this invention, spatial modulation would also be possible using an array of (NxM) of the QPI pixel modulation groups G_i such as that described in the previous design example. If, for example, it is required to create a directional light modulators of this invention with spatial modulation resolution of N = 16 by M = 16 that provides the $(9x128)^2$ = 147,456 directional modulation resolution of the previous example, the temporal spatio-optical directional light modulators of this invention would comprise an array of (16x16) directional modulation groups G_i and when a QPI with (5x5) micron pixel size is used, the total size of the temporal spatio-optical directional light modulator would be approximately 10.24x10.24 mm. Using the angular extent values of the previous example, the light emitted from such a spatio-optical directional light modulators of this invention can be spatially modulated at a resolution of (16x16) and directionally modulated at a resolution of 147,456 within the angular extent ±45°, and can also be modulated in color and intensity in each direction.

As illustrated by the previous examples, the spatial and directional modulation resolutions of the temporal spatio-optical light modulator in terms of the number of individually addressable directions within a given the angular extent would be determined by selecting the resolution and pixel pitch of the emissive micro emitter array QPI device 210, the pitch of the MLA 220 lens elements, the angular extent of the MLA 220 lens elements and the maximum articulation angle of the modulator gimbal. It is obvious to a person skilled in the art that the MLA lens system can be designed to allow either wider or narrower angular extent, the gimbal design can be selected to allow either wider or narrower articulation angle and the number of pixels within each modulation group can be selected either smaller or larger in order to create a temporal spatio-optical directional light modulator that can achieve any desired spatial and directional modulation capabilities following the teachings provided in the preceding discussion.

Any desired spatial and directional modulation capabilities can be realized using the spatio-optical directional light modulators of this invention. The previous example illustrated how spatio-optical directional light modulators of this invention with $(16)^2$ spatial resolution and $(3x128)^2$ directional resolution can be implemented using a single 10.24x10.24 mm QPI device 210. In order to realize higher spatial resolution, the temporal spatio-optical directional light modulators of this invention can be implemented using a tiled array comprising multiplicity of smaller spatial resolution temporal spatio-optical directional light modulators of this invention. For example, when an array of (3x3) of the temporal spatio-optical directional light modulator of the previous example are tiled as illustrated in Figure 11, the resultant temporal spatio-optical directional light modulators would provide $(3x16)^2$ spatial resolution and $(3x128)^2$ directional resolution. The tiling of a multiplicity of the temporal spatio-optical directional modulators of this invention in order to realize a higher spatial resolution version is possible because of its compact volumetric dimensions. For example, the temporal spatio-optical directional light modulator of the previous example that uses a single QPI device 210, which by itself would have an exemplary width, height and thickness of 10.24x10.24x5 mm; respectively, can be used to create the larger resolution version illustrated in Figure 11 which would have the dimension of 3.07x3.07x0.5 cm in width, height and thickness; respectively. If, for example, the tiling is expanded to include an array of (30x30) of the smaller resolution temporal spatio-optical directional light modulator, the resultant temporal spatio-optical directional light modulator would have a $(30x16)^2$ spatial resolution and $(3x128)^2$ directional resolution and would measure 30.07x30.07x0.5 cm in width, height and thickness, respectively. It would be possible to implement the higher spatial resolution version of the temporal spatio-optical directional light modulators of this invention illustrated is Figure 11 by bonding multiplicity of the temporal spatio-optical directional light modulators of the previous example to a backplane using electrical contacts of the micro ball grid array (MBGA) located on its backside, which given the zero-edge feature of embodiment 1600, would make it possible to realize seamless tiling of a multiplicity of such directional light modulator devices to implement any desired size of the temporal spatio-optical directional light modulators. Of course the size of the array of temporal spatio-optical directional light modulators illustrated in Figure 11 can be increased to the extent needed to realize any desired spatial resolution. It is also possible to tradeoff the directional resolution of the temporal spatio-optical directional light modulators for an increased spatial resolution. For example, if the pixel modulation group size is reduced to (64x64), the (3x3) array illustrated in Figure 11 would provide $(3x32)^2$ spatial resolution and $(3x64)^2$ directional resolution. It is worth noting that the array of temporal spatio-optical directional light modulators which offers the expanded spatial aperture illustrated in Figure 11 is made possible by the zero-edge feature described earlier of the temporal spatio-optical directional light modulator embodiment 1600 of this invention.

The principle of operation of the temporal spatio-optical directional light modulators will be described in reference to the illustrations of Figures 8 and 9. Figure 8 illustrates the two dimensional addressability of each of the modulation group G_i using m-bit resolution for the directional modulation. As explained earlier, light emitted from $(2^m x 2^m)$ individual pixels of the modulation group G_i is mapped by its associated MLA 220 elements into 2^{2m} light directions within the angular extent $\pm\Theta$ of the associated MLA micro lens element. Using the (x, y) dimensional coordinates of the individual pixels within each of the modulation groups G_i, the angular coordinates (θ, ϕ) of the emitted light beam is given by:

$$\theta(t) = \alpha_x(t) + \arctan\left[\frac{\sqrt{x^2+y^2} \times \tan(\Theta)}{0.5 \times (n-1)}\right] \qquad \text{Eq. 3}$$

$$\phi(t) = \alpha_y(t) + \arctan\left[\frac{y}{x}\right] \qquad \text{Eq. 4}$$

Where the $\alpha_x(t)$ and $\alpha_y(t)$ are values of the articulation angles around the x-axis and y-axis at the time epoch t; respectively, the angles $\theta(t)$ and $\phi(t)$ are the values of the directional modulation spherical coordinates at the time epoch t with the polar axis at $\Theta = 0$ parallel to the z-axis of the emissive surface of the modulation group G_i and $m = \log_2 n$ is the number of bits used to express the x and y pixel resolution within the modulation group G_i. The spatial resolution of the temporal spatio-optical directional light modulators of is defined the coordinates (X, Y) of each of the individual modulation group G_i within the two dimensional array of modulation groups comprising the overall temporal spatio-optical directional light modulator. In essence, the temporal spatio-optical light modulators would be capable of temporally generating (modulating) a light field described by the spatial coordinates (X, Y) defined by its modulation group array and the directional coordinates (θ,ϕ) with the latter being defined by the values of the coordinates **(x, y)** of the emissive pixels within the modulation group G_i and the temporal value of the articulation angle of the temporal spatio-optical directional light modulator as defined by Eq. 3 and 4 above.

Figure 10, which illustrates an exemplary embodiment of the data processing block diagram of the spatio-optical directional light modulator, is also applicable to the temporal spatio-optical embodiments of the invention. The prior description of using 16-bit for representing the directional modulation and the typical 24-bit for representing the modulated light intensity and color in each direction is also applicable to the temporal spatio-optical embodiments of this invention.

Possible Applications Include

The temporal spatio-optical directional light modulators of this invention can be used to implement a 3D display with an arbitrary size that is realized, for example, as a tiled array of multiplicity of temporal spatio-optical directional light modulator devices such as that illustrated in Figure 11. The expanded angular extent that can be realize by the temporal spatio-optical directional light modulators would enable the realization of 3D displays that are volumetrically compact and provide a large viewing angle, yet without the use of bulky and costly optical assemblies. The level of volumetric compactness that can be achieved by the temporal spatio-optical directional light modulators will enable the realization of both desk top as well as possibly mobile 3D displays. Furthermore, the expanded directional modulation capabilities of the temporal spatio-optical directional light modulators makes it capable of modulating within its expanded angular extent a multiplicity of views with an angular resolution value of 5Θ that is commensurate with the human visual system eye angular separation, thus making it a 3D display that will not require the use of glasses to view the 3D content it display. In fact, given the high number of independently modulated light beams the temporal spatio-optical directional light modulator of this invention can generate, it would be capable of modulating a 3D image with sufficient angular resolution value between the generated multiple views that will eliminate the vergence-accommodation conflict (VAC) which typically hinders the performance of 3D displays and cause visual fatigue. In other words, the angular resolution capabilities of the temporal spatio-optical directional light modulators of this invention make them capable of generating a VAC-free 3D images that will not cause viewers' visual fatigue. The light field modulation capabilities of the temporal spatio-optical directional light modulators also make it the underlying bases of 3D light field displays that can be used to implement a synthetic holography 3D displays.

The temporal spatio-optical directional light modulators can also be used as a backlight for liquid crystal display (LCD) to implement a 3D display. The temporal spatio-optical directional light modulators can also be operated as a 2D high resolution display. In this case the individual pixels of the QPI device 210 would be used to modulate the color and intensity while the MLA 220 would be used to fill the viewing angle of the display. It is also possible for the temporal spatio-optical light modulators to be switched from 2D to 3D display modes by adapting the format of its input data to be commensurate with the desired operational mode. When the temporal spatio-optical directional light modulator is used as a 2D display its light angular extent will be that of associate with its MLA 220 micro lens element plus the articulation angle of its gimbal $\pm(\Theta + \alpha_{max})$ with the pixel resolution of the individual modulation group G_i leveraged to achieve higher spatial resolution.

Thus the present invention has a number of aspects, which aspects may be practiced alone or in various combinations or sub-combinations, as desired. While certain preferred embodiments of the present invention have been disclosed and described herein for purposes of illustration and not for purposes of limitation, it will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the full breadth of the following claims.

CLAIMS

What is claimed is:

1. A light modulator comprising:

an emissive micro emitter array device having a micro array of pixels, and

a micro lens array, each micro lens in the micro lens array spanning a group of pixels of the emissive micro emitter array, whereby a micro lens in the micro lens array will direct illumination from each emissive micro emitter in the respective group of pixels in a different direction.

2. The light modulator of claim 1 wherein each group of pixels is a two dimensional group of pixels.

3. The light modulator of claim 2 wherein each of the pixels of the emissive micro emitter array device is a solid state light emitter that is individually addressable, the solid state light emitter being selected from the group consisting of light emitting diodes and laser diodes.

4. The light modulator of claim 3 wherein each pixel of the emissive micro emitter array device may emit light of multiple colors, and each pixel is individually addressable to emit light of a selected color and intensity.

5. The light modulator of claim 3 wherein the pixels of the emissive micro emitter array device have a linear dimension of ten microns or less.

6. The light modulator of claim 3 wherein the micro lens array is comprised of a plurality of stacked micro lens arrays

7. The light modulator of claim 4 wherein the direction, color and intensity addressability of the light modulator is accomplished using a multiple field data input to the light modulator, whereby for each designated pixel group address within the spatial array of the pixel groups, at least one input data field is used to specify the direction of the emitted light and at least one field is used to specify the color and intensity of the light emitted in that designated direction.

8. The light modulator of claim 4, in plurality, comprising a tiled array of light modulators.

9. The light modulator of claim 4 in plurality, comprising a collective set of light modulators in a tiled array, wherein in each light modulator, the pixels of the emissive micro emitter array device are multicolor pixels and are individually addressable to emit light with a selected color and intensity, the micro lens array is comprised of a plurality of stacked micro lens arrays, each of the lenses of the micro lens array is associated and aligned with a plurality of pixels within a respective pixel group of the respective emissive micro emitter array device, with each lens optically mapping the light emitted from the plurality of pixels into a corresponding discrete set of directions within a numerical aperture of the lens to enable the of color and intensity of the light emitted in each individual direction of the discrete set of directions, thereby enabling the light modulator to generate light that is modulated in color, intensity and direction across an aperture spanning the collective set of light modulators.

10. The light modulator of claim 4 wherein the direction, color and intensity addressability of each pixel of the light modulators is accomplished using a multiple field data input to the individual light modulators, whereby for each designated pixel group address within the spatial array of the pixel groups, at least one input data field is used to specify the spatial direction of the emitted light and at least one field is used to specify the color and intensity of the light emitted in that designated direction.

11. The light modulator of claim 4 wherein the light modulator can be switched to operate either as a 3D display or as a high resolution 2D display by adapting the format of the multiple field data input to be commensurate with the desired operational mode.

12. The light modulator of claim 4 in a liquid crystal display as a backlight for the liquid crystal display to create either a 3D display or 2D display.

13. The light modulator of any of claims 1 through 12 wherein the different directions of illumination from the emissive micro emitters define an angular extent, and wherein the emissive micro emitter array device and the micro lens array are assembled together and are angularly articulated as a single assembly about at least one axis to emit light within a plane of an emissive surface of the emissive micro emitter array and within a range of plus and minus a maximum angular articulation.

14. The light modulator of claim 13 wherein the emissive micro emitter array device and the micro lens array are configured to be angularly articulated as a single assembly about two orthogonal axes within a range of plus and minus a maximum angular articulation about the respective axis.

15. The light modulator of claim 14 wherein the angular articulation is configured to either increases an angular resolution between the different directions, or increases the angular extent of the different directions of illumination from the emissive micro emitters.

16. The light modulator of claim 13 wherein adjacent light modulators in the tiled array have some inactive edge pixels between active pixels in adjacent groups of pixels.

17. The light modulator of claim 3 wherein:

the pixels of the emissive micro emitter array device are multi color pixels and are individually addressable to emit light with a selected color and intensity;

the micro lens array has a plurality of stacked micro lens arrays, each of the lenses of the micro lens array is associated and aligned with a plurality of pixels within a pixel group of the emissive micro emitter array device, with each lens optically mapping the light emitted from the respective plurality of pixels into a corresponding discrete set of directions within a numerical aperture of the respective lens to enable the of color and intensity of the light emitted in each individual direction of set of the discrete set of directions:

thereby enabling the light modulator to generate light that is modulated in color, intensity and direction.

18. The light modulator of claim 1, in plurality, comprising a tiled array of light modulators.

19. The light modulator of claim 1 wherein the light modulator can be switched to operate either as a 3D display or as a high resolution 2D display by adapting the format of the multiple field data input to be commensurate with the desired operational mode.

20. A directional light modulator comprising:

a two dimensional emissive micro emitter array device;

a micro lens array of micro lens elements;

the two dimensional emissive micro emitter array device and the micro lens array being assembled together and angularly articulated as a single assembly to emit light around two axes within a plane of an emissive surface of the emissive micro emitter array and within a range of plus and minus a maximum angular articulation in each respective axis.

21. The directional light modulator of claim 20 wherein the two dimensional emissive micro emitter array comprises an array of pixels wherein each pixel is a solid state light emitter that is individually addressable.

22. The directional light modulator of claim 21 wherein each pixel of the two dimensional emissive micro emitter array has dimensions not exceeding 20 by 20 microns.

23. The directional light modulator of claim 21 wherein each pixel is individually addressable to modulate light it emits in both color and intensity.

24. The directional light modulator of claim 20 wherein the angular articulation is provided by a gimbal support for the assembly of the two dimensional emissive micro emitter array device and the micro lens array for temporally

expanding the angular extent in each of the two axes by the angular articulation of the gimbal support, thereby temporally expanding the set of light directions along each of the two axes.

25. The directional light modulator of claim 24 wherein the temporally expanded angular extent is temporally continuous or discrete and has a repetition rate that is proportional to and synchronized with an image input data frame rate, whereby the maximum angular articulation around each of the two axes determines the expanded angular extent of the directional light modulator, the angular coverage, shape and aspect ratio.

26. The directional light modulator of claim 25 wherein the angular articulation around each of the two axes is at least equal to a frame rate of the input image data multiplied by a factor that equals the ratio of the expanded angular extent to the angular extent along each respective axis.

27. The directional light modulator of claim 24 wherein the addressability of each pixel is accomplished using a multiple field data input to the directional light modulator whereby for each designated pixel group address within the spatial array of the pixel groups, at least one input data field is used to specify the direction of the emitted light and at least one field is used to specify the color and intensity of the light emitted in that designated direction.

28. The directional light modulator of claim 20 being used as a display that can be switched to operate either in a 3D display mode or in a high resolution 2D display mode by adapting a format of input data to be commensurate with the desired mode.

29. The directional light modulator of claim 20 used as a backlight for a liquid crystal display (LCD) that can be switched to operate either as a 3D display or as a high resolution 2D display.

30. The directional light modulator of claim 20 capable of modulating within its expanded angular extent a multiplicity of views with an angular resolution

value commensurate with the human visual system eye angular separation, thus making it a 3D display that will not require the use of glasses to view the 3D content it displays.

31. A directional light modulator comprising:

an emissive micro emitter array device comprising a multiplicity of pixels;

a micro lens array aligned and physically bonded to the emissive micro emitter array device; and,

the two axis gimbal having two sets of electromagnetic actuators aligned with the two axes of the gimbal to affect temporal angular articulation of said bonding pad around the two axes of the gimbal.

32. The directional light modulator of claim 31 wherein the two axis gimbal is implemented using multiple silicon substrate layers to realize a two axis pivot of the gimbal and a mechanical resistance spring that defines the neutral position of the gimbal relative to a gimbal base.

33. The directional light modulator of claim 32 wherein drive electrical signals to the electromagnetic actuators provide temporal angular articulation that is either temporally continuous or discrete and having a repetition rate that is proportional to and synchronized with an image input data frame rate provided through the device interface contacts, and wherein the drive electrical signals include correction values provided by a set of sensors bonded to a backside of the contact pad and a topside of a base layer of the gimbal.

34. The directional light modulator of claim 31 wherein the two axis gimbal comprises a spherical pivot on the backside of the bonding pad and a matched spherical socket on a topside of a gimbal base.

35. The directional light modulator of claim 31 wherein in the micro lens array, each of its constituent lenses is associated and precisely aligned with a respective plurality of pixels within a two dimensional array of pixel groups, with each constituent lens optically mapping the light emitted from the respective

plurality of pixels into a corresponding discrete set of directions within an angular extent defined by a numerical aperture of the respective constituent lens.

36. The directional light modulator of claim 31, used in plurality to form a tiled array of the directional light modulators having an expanded spatial aperture.

37. The directional light modulators of claim 36 wherein in the micro lens arrays, each of its constituent lenses is associated and precisely aligned with a respective plurality of pixels within a two dimensional array of pixel groups, with each constituent lens optically mapping the light emitted from the respective plurality of pixels into a corresponding discrete set of directions within an angular extent defined by a numerical aperture of the respective constituent lens, and further comprised of a collective set of the spatial arrays of the pixel groups whereby each pixel within each pixel group is individually addressable to generate light that is modulated in color, intensity and direction, thereby enabling the expanded spatial aperture directional light modulator device to generate spatially modulated light across a spatial aperture spanning the collective set of the spatial arrays that is also modulated in color, intensity and direction.

38. The directional light modulators of claim 37 being used as a backlight for a liquid crystal display (LCD) to create either a 3D display or 2D display that can be switched to operate either as a 3D display or as a high resolution 2D display.

39. The directional light modulators of claim 37 capable of modulating within its expanded angular extent a multiplicity of views with an angular resolution value commensurate with the human visual system eye angular separation, thus making it a 3D display that will not require the use of glasses to view the 3D content it displays.

40. The directional light modulator of claim 31 being used as a backlight for a liquid crystal display (LCD) to create either a 3D display or 2D display that can be switched to operate either as a 3D display or as a high resolution 2D display.

41. The directional light modulator of claim 31 wherein light field modulation capabilities of the directional light modulator makes it the underlying basis of a 3D light field display that can be used to implement a synthetic holography 3D display.

42. A method of forming a directional light modulator comprising:

providing an emissive micro emitter array device;

providing a micro lens array of micro lens elements;

aligning the micro lens array with the emissive micro emitter array device into a direction light modulator subassembly so that each micro lens element of the micro lens array is associated and aligned with a corresponding plurality of micro emitters within a two dimensional array of micro emitters of the emissive micro emitter array device to emit light around two axes within the plane of an emissive surface of the emissive micro emitter array within a range of plus or minus a maximum angular extent, whereby each micro lens element optically maps light emitted from the corresponding plurality of micro emitters into a corresponding discrete set of directions within an angular extent defined by a numerical aperture of each micro lens element;

temporally articulating the directional light modulator subassembly about at least a first axis in a plane of the assembly to expand the discrete set of directions responsive to the angular articulation.

43. The method of claim 42 wherein the directional light modulator subassembly is also articulated about a second axis in the plane of the assembly to further expand the discrete set of directions responsive to the angular articulation, the second axis being perpendicular to the first axis.

44. The method of claim 43 wherein:

providing an emissive micro emitter array device comprises providing a matrix of micro emitter array devices on a single substrate;

providing a micro lens array comprises providing a matrix of micro lens arrays;

mounting the matrix of micro lens arrays onto the matrix of micro emitter array devices to form a matrix of directional light modulators, and;

dicing the matrix of directional light modulators to provide a plurality individual directional light modulators.

45. The method of claim 44 wherein the matrix of micro lens arrays are aligned with respect to the matrix of micro emitter array devices to form a matrix of directional light modulators using semiconductor wafer level alignment techniques.

46. The method of claim 44 wherein providing the matrix of micro lens arrays comprises providing a plurality of micro lens array layers, wherein the micro lens array layers are mounted in a stack and aligned with respect to each other to form the matrix of micro lens arrays.

47. The method of claim 44 wherein each micro emitter is individually addressable to control the color and brightness thereof.

48. The method of claim 47 wherein light emitted from the corresponding plurality of micro emitters into a corresponding discrete set of directions within an angular extent defined by a numerical aperture of each micro lens element forms a corresponding pixel group, the association of the pixels within each pixel group with the temporally expanded set of directions together with the individual pixel addressability enabling the individual addressability the temporally expanded set of directions, whereby the directional light modulator generates light that is directionally modulated in any of the directions comprising the set of the temporally expanded set of light directions.

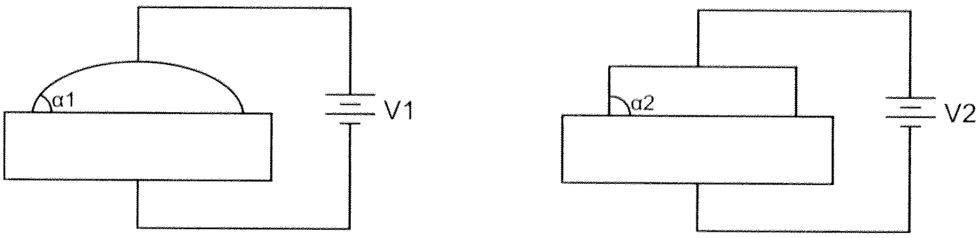

Figure 1 (Prior Art)

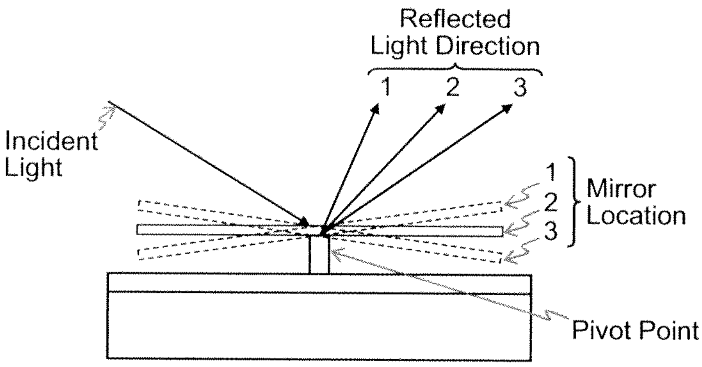

Figure 2 (Prior Art)

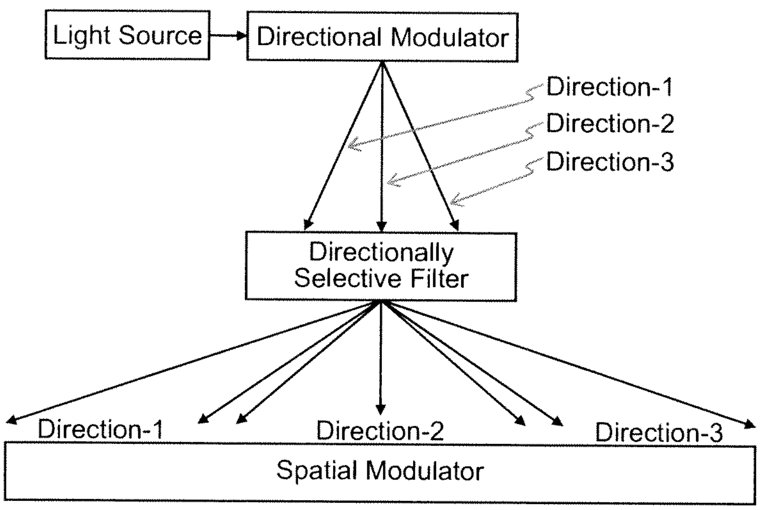

Figure 3 (Prior Art)

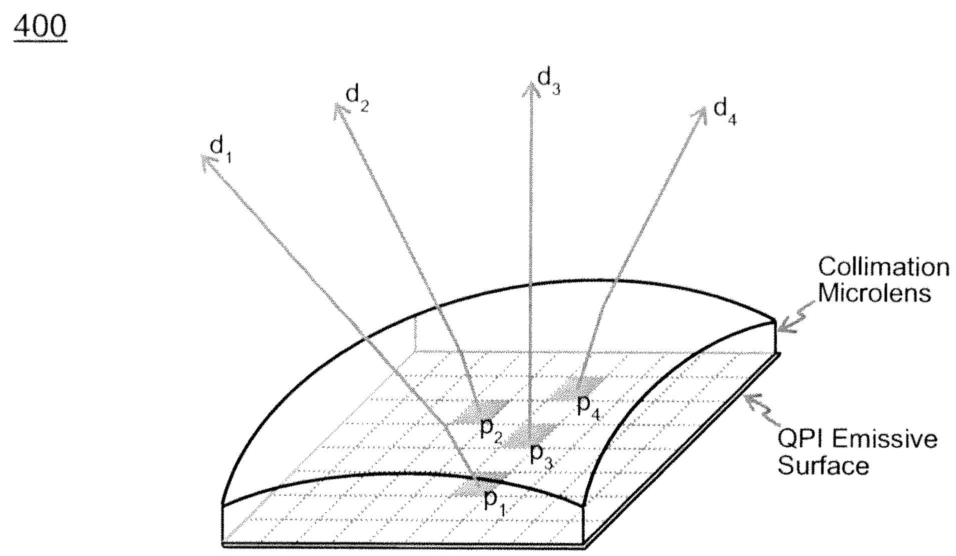

Figure 4

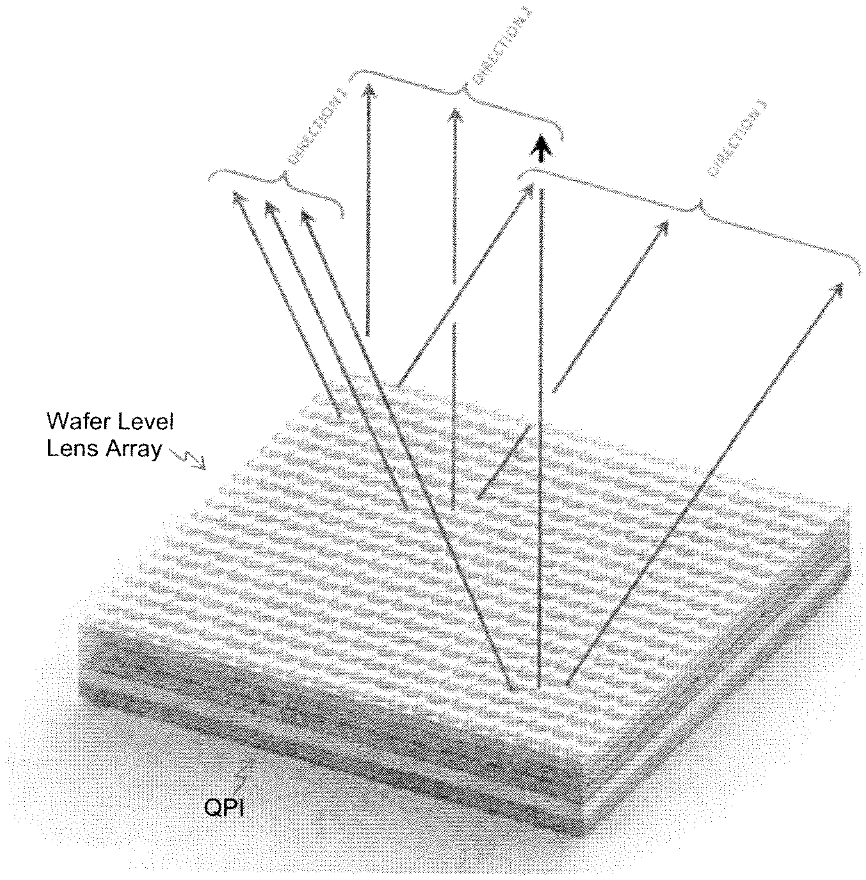

Figure 5

600

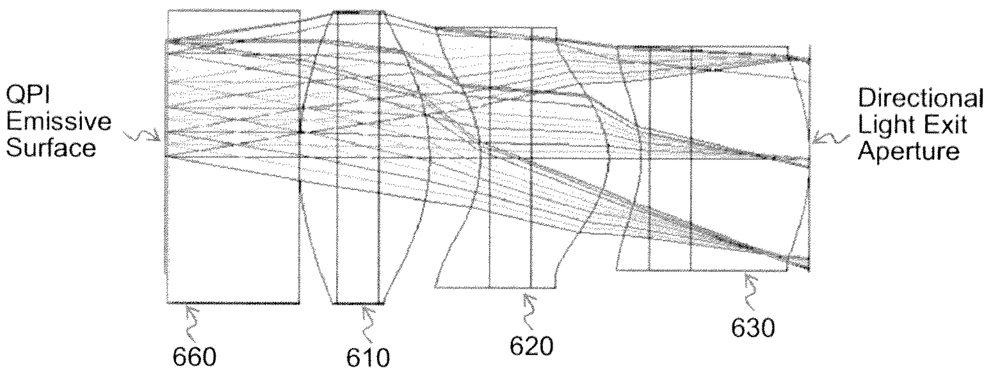

Figure 6

700

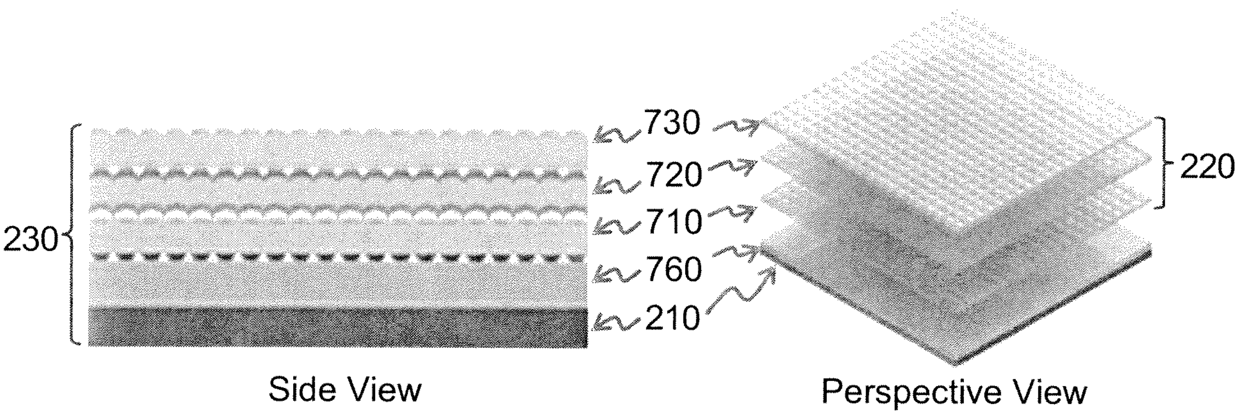

Figure 7

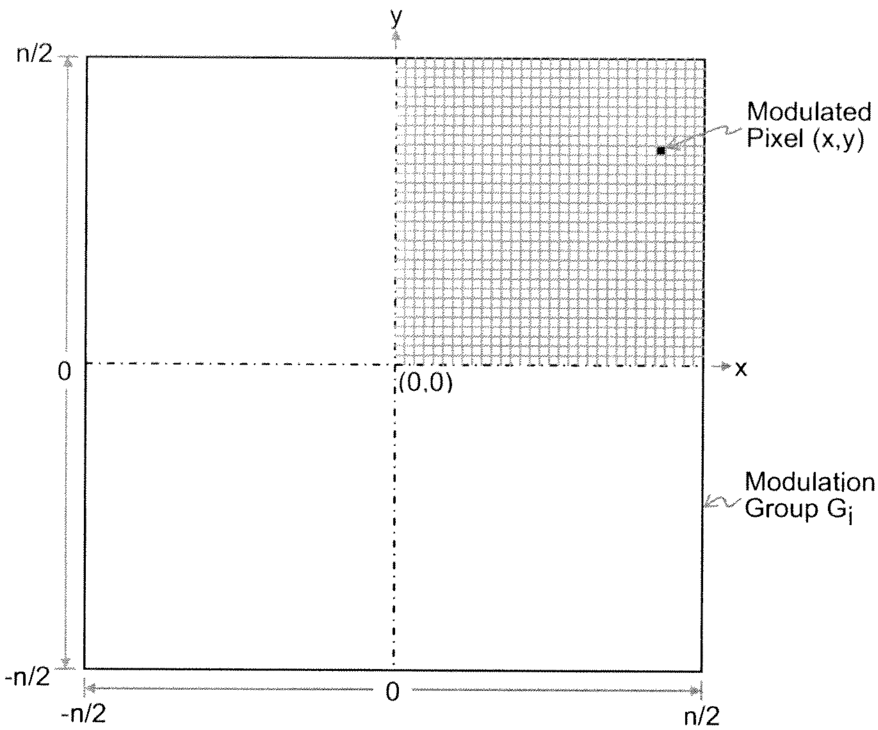

Figure 8

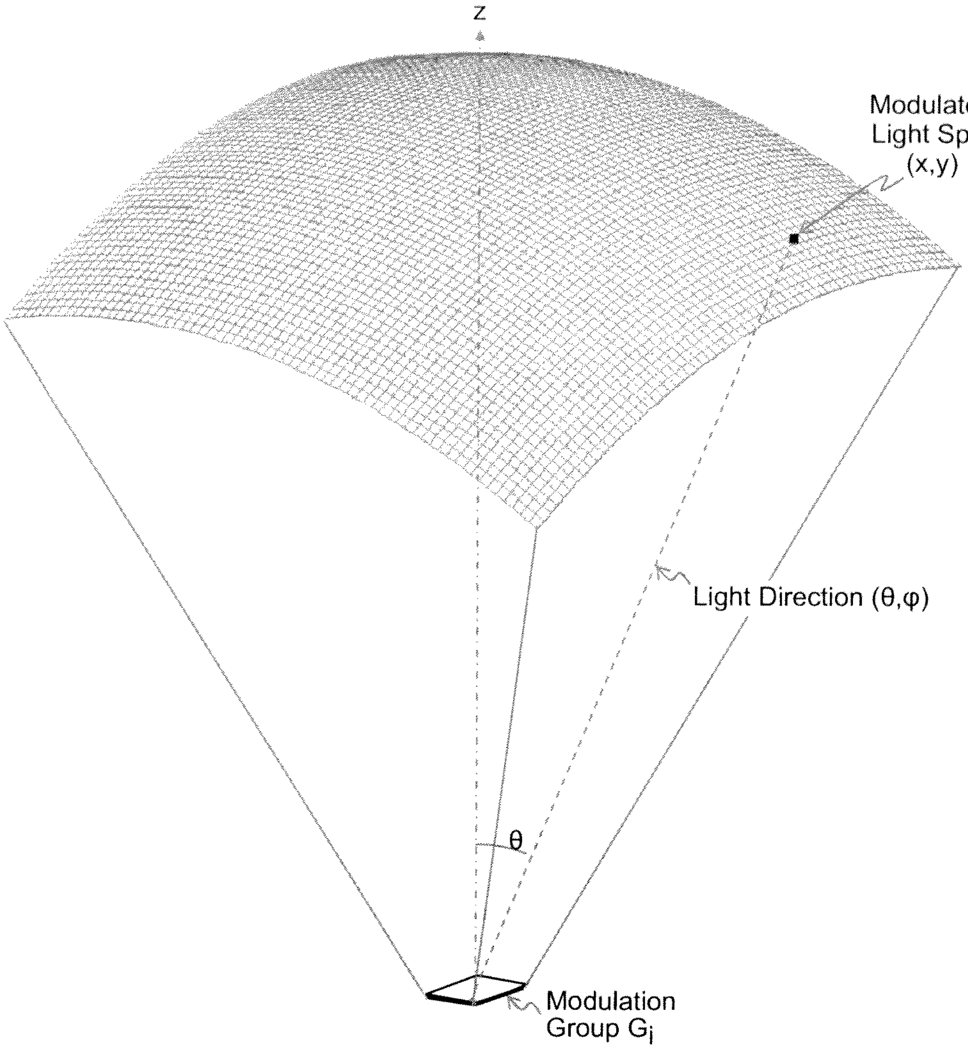
z
Modulated
Light Spot
(x,y)
Light Direction (θ,φ)
θ
Modulation
Group G_i

Figure 9

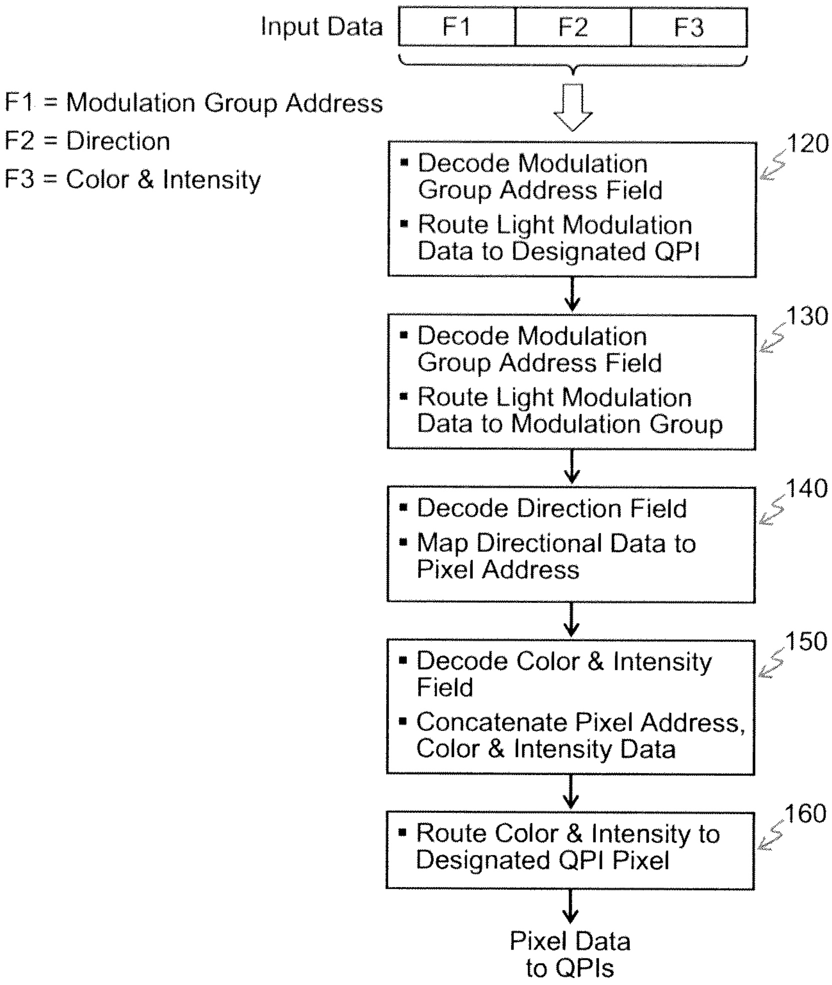
Input Data
F1
F2
F3
F1 = Modulation Group Address
F2 = Direction
F3 = Color & Intensity
Decode Modulation Group Address Field
Route Light Modulation Data to Designated QPI
120
Decode Modulation Group Address Field
Route Light Modulation Data to Modulation Group
130
Decode Direction Field
Map Directional Data to Pixel Address
140
Decode Color & Intensity Field
Concatenate Pixel Address, Color & Intensity Data
150
Route Color & Intensity to Designated QPI Pixel
160
Pixel Data to QPIs

Figure 10

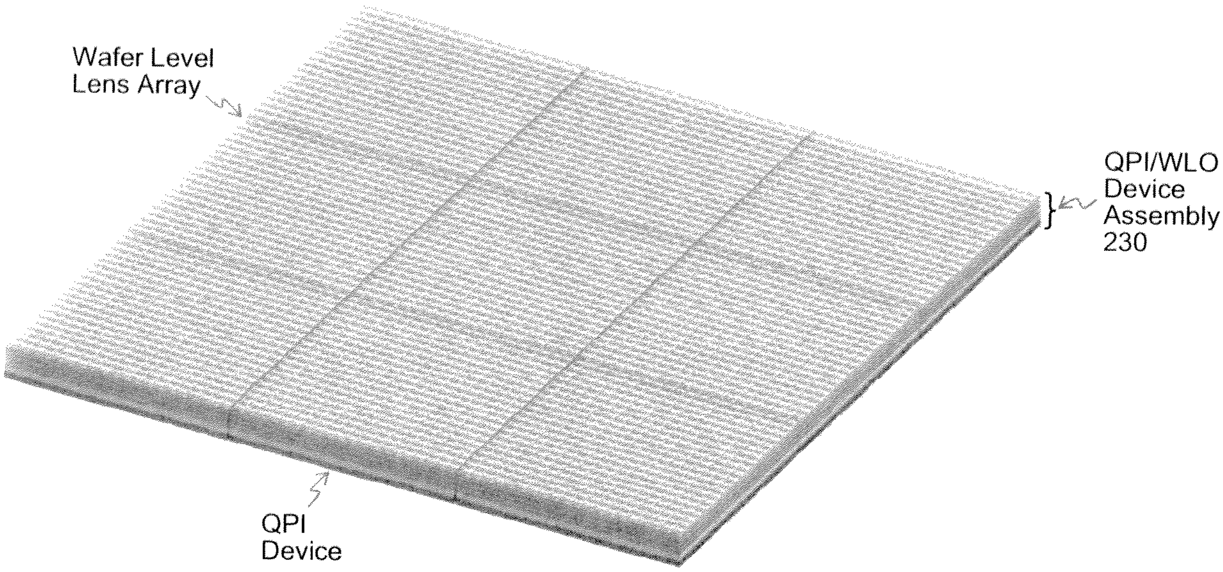

Figure 11

200

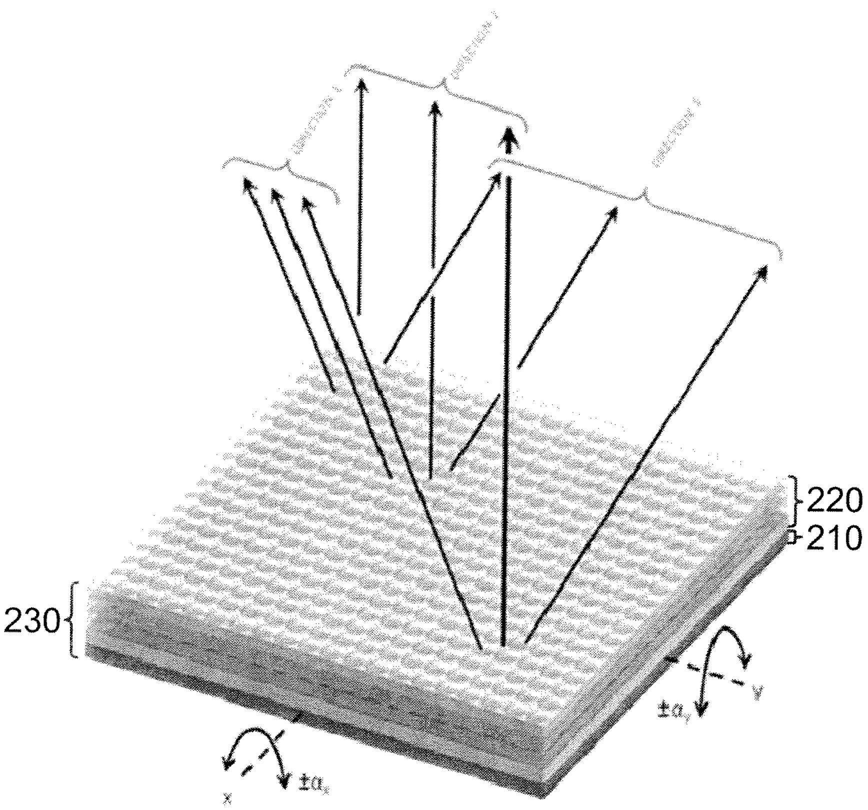

Figure 12

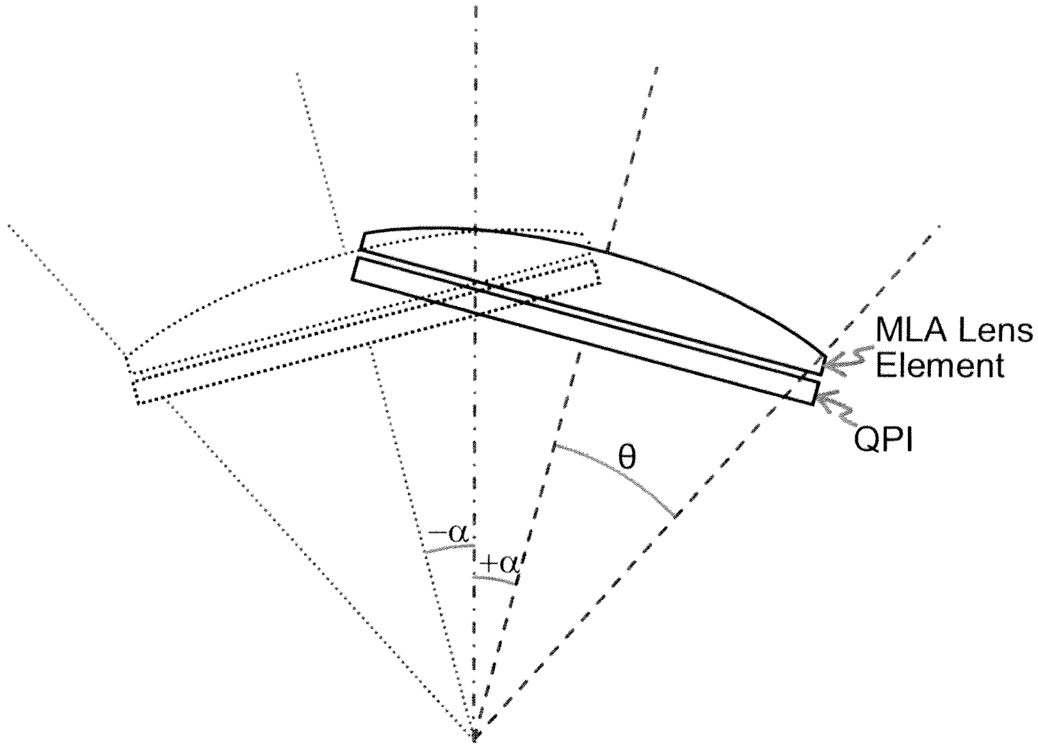

Figure 13A

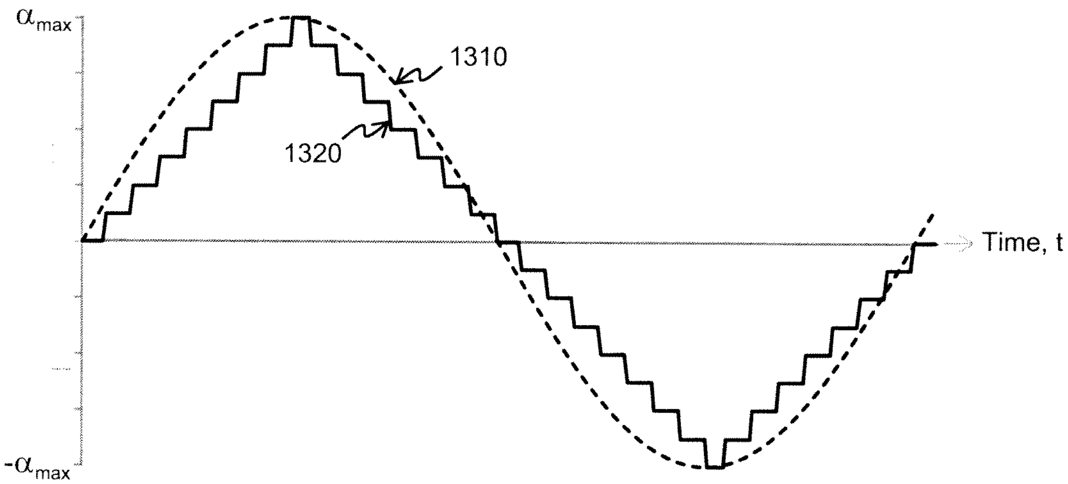

Figure 13B

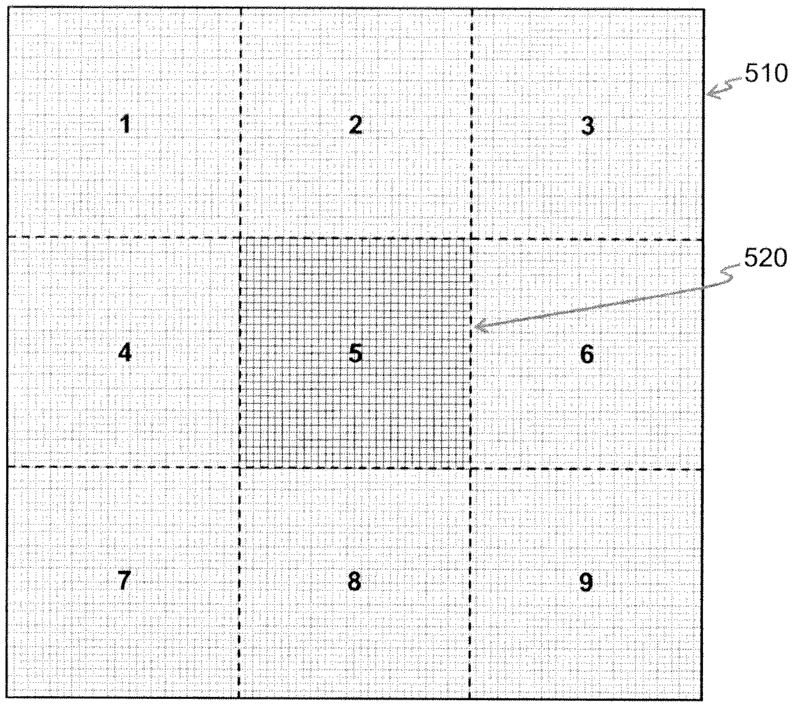

Figure 14

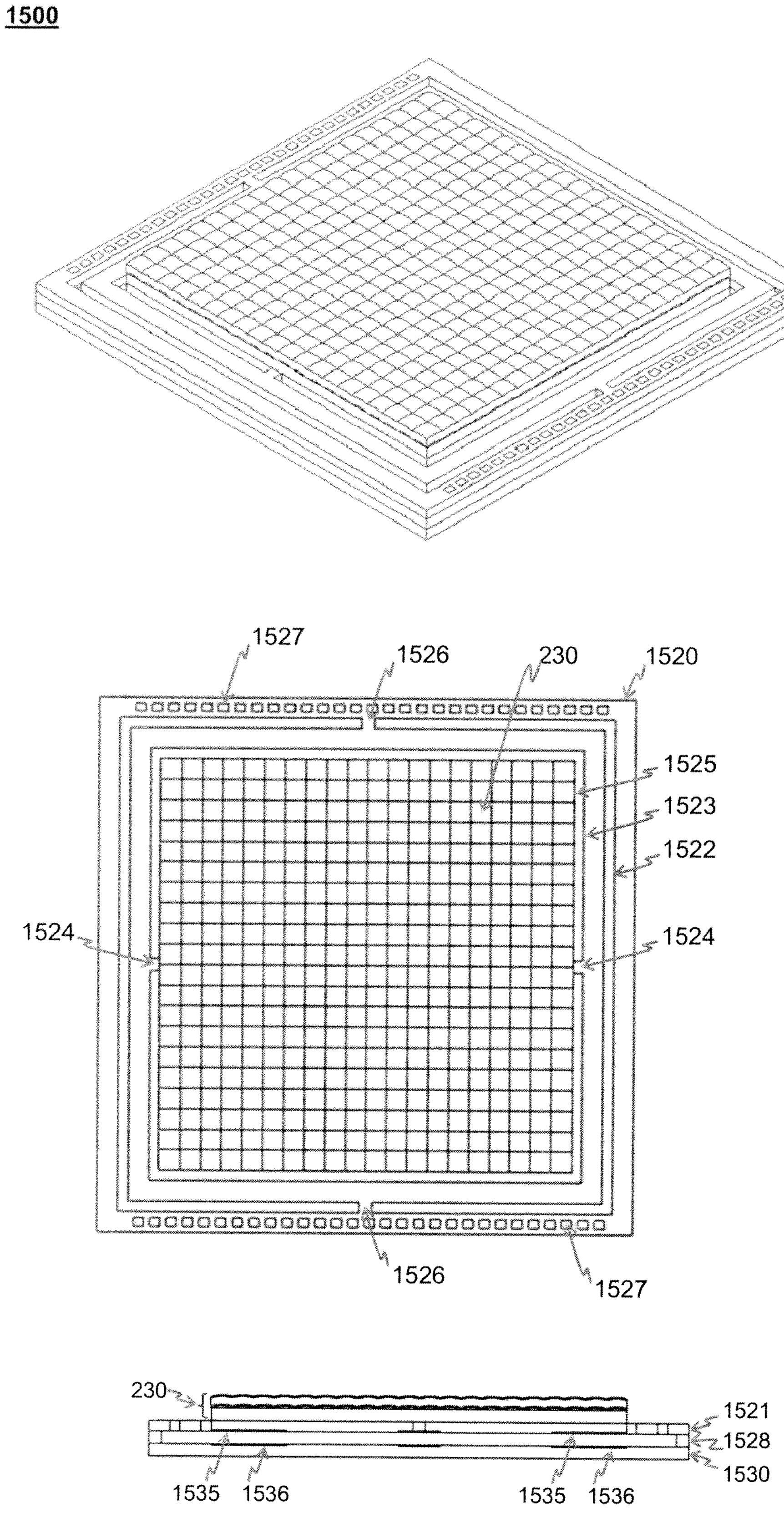
1500
1527
1526
230
1520
1525
1523
1522
1524
1524
1526
1527
230
1521
1528
1530
1535
1536
1535
1536

Figure 15

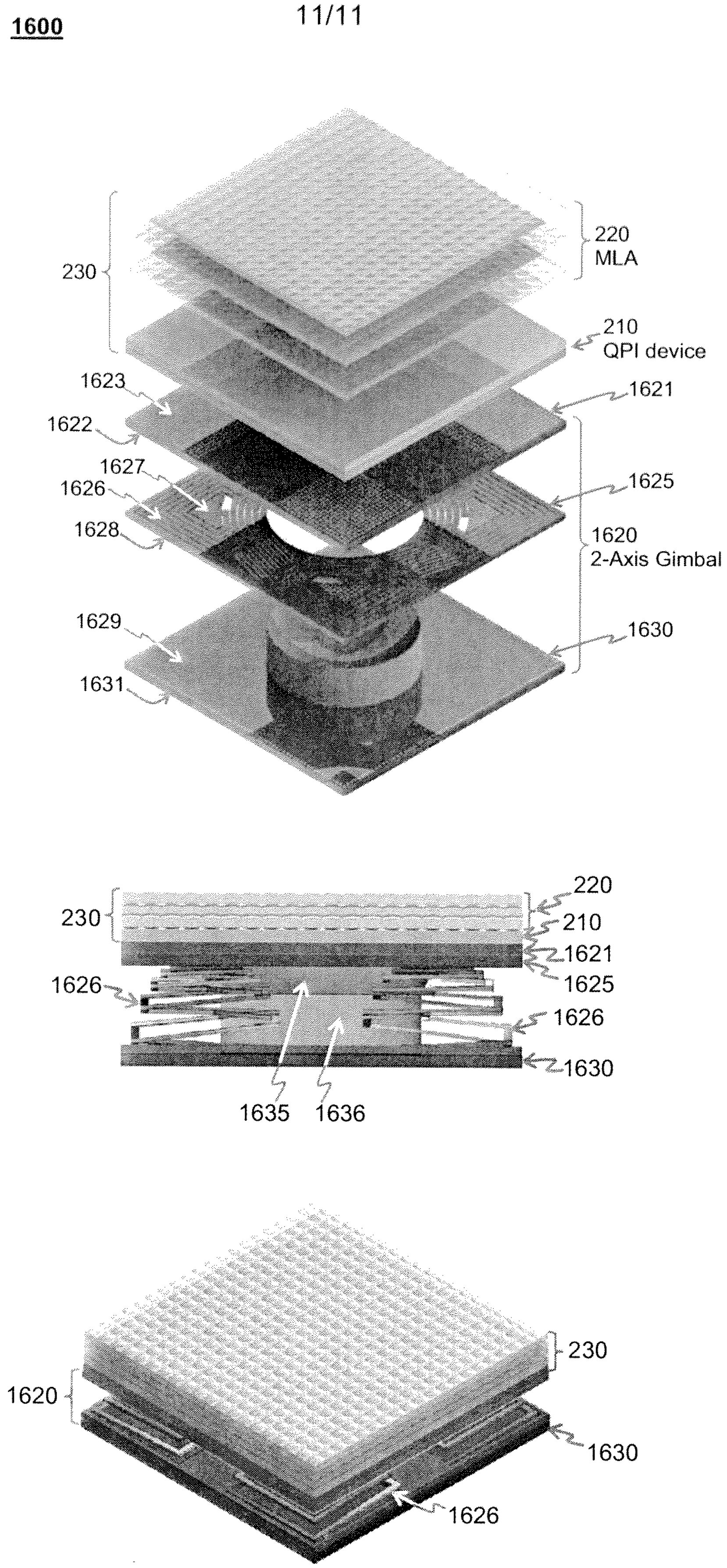
1600
230
220
MLA
210
QPI device
1623
1621
1622
1627
1625
1626
1628
1620
2-Axis Gimbal
1629
1630
1631
230
220
210
1621
1625
1626
1626
1630
1635
1636
230
1620
1630
1626

Figure 16

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/068029

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B27/22 H04N13/04 G02B26/08 G02B3/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B H04N

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

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

EPO-Internal , INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/096156 Al (KIM J00-Y0UNG [KR] ET AL) 28 April 2011 (2011-04-28)	1-5, 7-12, 16-19
Y	paragraph [0056] - paragraph [0066]; figure 2	6, 13-15
Y	US 6 795 241 Bl (H0LZBACH MARK E [US]) 21 September 2004 (2004-09-21) figure 5	6
Y	JP 2008 304572 A (HIGUCHI T0SHI R0; G0ND0 MASAHI K0; T0KAI RI KEN KK) 18 December 2008 (2008-12-18) abstract; figures 3-6	13-15
Y	US 5 059 008 A (FLOOD KEVIN M [US] ET AL) 22 October 1991 (1991-10-22) abstract; figure 5a	20-48

-/-

[X] Further documents are listed in the continuation of Box C.

[X] 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
13 March 2013	19/03/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lehtiniemi, Henry

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/068029

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/109813 A1 (COPELAND STEVE A [CA] ET AL) 17 May 2007 (2007-05-17) abstract; figures 1-3 -----	20-48
A	JP 2010 117398 A (SEIKO EPSON CORP) 27 May 2010 (2010-05-27) abstract; figures 6,7,9 -----	6

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2012/068029

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			JP 2011095730	A	12- 05-2011
			KR 20110046127	A	04-05-2011
			US 2011096156	AI	28-04-2011
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JP 2008304572	A	18-12-2008	JP 5074103	B2	14-11-2012
			JP 2008304572	A	18-12-2008
us 5059008	A	22-10-1991	NONE		
us 2007109813	AI	17-05-2007	CA 2568128	AI	15-05-2007
			US 2007109813	AI	17-05-2007
JP 2010117398	A	27-05-2010	NONE		