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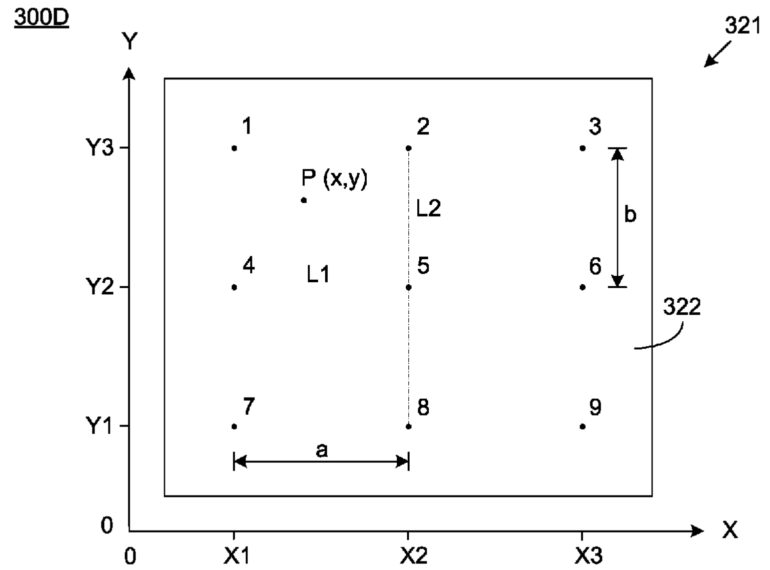

FIG. 3D

(57) **Abstract:** A display device includes a display panel, a first light source, and second light source. The first and second light sources are respectively aligned with a first spot and second spot in a direction perpendicular to a substrate. The first light source irradiates the first and second spots with luminance of a first value and second value, respectively. The first light source irradiates a midpoint between the first and second spots with a luminance value that is half the addition of the first and second values.

WO 2023/133687 A1

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BACKLIGHT MODULE AND DISPLAY DEVICE II

FIELD OF INVENTION

[0001] The present disclosure generally relates to a backlight module and a display device including the backlight module and, specifically, to a backlight module that uses lenses to improve luminance uniformity.

BACKGROUND OF THE INVENTION

[0002] Liquid crystal display (LCD) devices have been widely used throughout the industry and in people's daily life. A LCD device has a LCD panel and a backlight module. The LCD panel receives light from the backlight module and displays an image by adjusting the light transmittance through pixels made of liquid crystal elements. There are direct-type and edge-type backlight modules. For a direct-type backlight module, the light source is disposed facing the rear surface of the LCD panel, irradiating the LCD panel directly. For an edge-type backlight module, the light source is disposed on a side of the LCD panel. A light-guiding plate is disposed adjacent to the rear surface of the LCD panel and guides the light to irradiate the LCD panel. In descriptions below, direct-type backlight modules are described.

[0003] In a direct-type backlight module, an array of light emitting diode (LED) is often used as the light source. As regions immediately over the LEDs are brightly irradiated, while regions between the LEDs are dimly irradiated, uneven luminance becomes an issue, especially when LCD devices are getting thinner and thinner. As a consequence, more LEDs are needed to improve luminance uniformity, causing an increase of the manufacturing cost. The present disclosure has been made in view of the above-described problems.

SUMMARY OF THE INVENTION

The present disclosure discloses methods and apparatus for a backlight module and a display device that contains the backlight module. In one aspect, a display device includes a display panel, a substrate disposed proximate to the display panel, a plurality of LED light sources disposed on the substrate following a grid pattern to form a plurality of rectangle-shaped lighting units, wherein each lighting unit comprises four LED light sources disposed at the lighting unit's four corners, respectively, has a length L along a first direction X and a width W along a second direction Y, and irradiates a corresponding rectangular area with the same length L and width W on an interface of the display device, wherein each LED light source comprises an LED and a corresponding lens disposed above the LED, the corresponding lens directing light rays emitted from the LED onto

(1) a first corner of the corresponding rectangular area on the interface of the display device with a first luminance value E1,

(2) a second corner of the corresponding rectangular area with luminance of a first predetermined value, wherein a distance between the first corner and the second corner is L along the X direction,

(3) a first location (x, 0) with a luminance value E (x, 0) that is determined based on a change of luminance value from the first luminance value E1 at the first corner to the first predetermined value at the second corner, wherein the first location is on a first border line between the first corner and the second corner, and x is a distance between the first location (x, 0) and the first corner along the X direction,

(4) a third corner of the corresponding rectangular area with luminance of a second predetermined value, wherein a distance between the first corner and the third corner is W along the Y direction,

(5) a second location (0, y) with a luminance value E (0, y) that is determined based on a change of luminance value from the first luminance value E1 at the first corner to the second predetermined value at the third corner, wherein the second location is on a second border line between the first corner and the third corner, and y is a distance between the second location (0, y) and the first corner along the Y direction, and

(6) a third location (x, y) of the corresponding rectangular area with a luminance value of E (x, y) that is a product of E (x, 0) and E (0, y).

[0004] In another aspect, a backlight module includes a substrate, a first light source disposed on the substrate, a second light source disposed on the substrate and adjacent to the first light source, a first lens, and a second lens. The first light source, the first lens, and a first spot are aligned along a direction approximately perpendicular to the substrate. The second light source, the second lens, and a second spot are aligned along the direction. Light emitted from the first light source passes through the first lens to irradiate the first spot with luminance of a first value, irradiate the second spot with luminance of a second value, and irradiate a middle spot with luminance of a value that is half of addition of the first and second values or substantially close to half of addition of the first and second values. The middle spot is between the first spot and the second spot.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The subject matter, which is regarded as the invention, is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features and also the advantages of the invention will be apparent from the following detailed description taken in conjunction with the accompanying drawings. Additionally, the leftmost digit of a reference number identifies the drawing in which the reference number first appears.

[0006] Figure 1 is a perspective view of a prior art LCD device.

[0007] Figure 2A schematically illustrates a cross-sectional view of a display device, according to embodiments of the present disclosure.

[0008] Figures 2B and 2C schematically illustrate a cross-sectional view and a top view of a backlight module of the display device shown in Figure 2A, according to embodiments of the present disclosure.

[0009] Figure 3A schematically illustrates light sources of a backlight module in a top view, according to embodiments of the present disclosure.

[0010] Figures 3B and 3C schematically illustrate cross-sectional views corresponding to the backlight module shown in Figure 3A, according to embodiments of the present disclosure.

[0011] Figure 3D schematically shows certain spots on an interface over of the light sources shown in Figure 3A, according to embodiments of the present disclosure.

[0012] Figures 3E and 3F schematically show two luminance curves reflecting linear changes of luminance.

[0013] Figure 3G schematically shows a diagram of a light path corresponding to the configuration shown in Figure 3B.

[0014] Figures 3H, 3I, 3J, 3K, and 3L schematically show the intensity of light emitted from a light source of the backlight module with regard to Figures 3A-3D.

[0015] Figure 4 shows a diagram of light passing through a concave lens.

[0016] Figure 5 shows a diagram of light irradiating a surface via a lens.

[0017] Figures 6A and 6B schematically show luminance curves reflecting changes of luminance under different conditions.

[0018] Figures 7A and 7B schematically illustrate light sources arranged in different configurations, according to embodiments of the present disclosure

[0019] Figure 8 illustrates a flow chart for designing a lens for a backlight module, according to embodiments of the present disclosure.

[0020] Figure 9 illustrates a flow chart for assembling a backlight module and a display device, according to embodiments of the present disclosure.

[0021] Figure 10 illustrates a structural diagram of a display device, according to embodiments of the present disclosure.

DETAILED DESCRIPTION

[0022] Detailed description of the present invention is provided below along with figures and embodiments, which further clarifies the objectives, technical solutions, and advantages of the present invention. It is noted that schematic embodiments discussed herein are merely for illustrating the invention. The present disclosure is not limited to the embodiments disclosed.

[0023] Figure 1 shows a prior art display device 100 in a perspective view. The display device 100 has a LCD panel 110, a section 111 that contains a filter unit and a diffuser, a spacer layer 112, and a section 113 that contains a mini-LED array. The filter unit contains color filter elements that convert an incident light into light of different wavelengths, respectively. The diffuser may include a layer of a diffusion material, diffuse light passing through it, and improve luminance uniformity by reducing the luminance of bright portions of the light. The layer 112 may be made of an adhesive material such as resin that is transparent to the light.

[0024] During operation of the display device 100, light emitted from the mini-LED array in the section 113 spreads in and passes through the layer 112, before irradiating the section 111 or the diffuser. Because the layer 112 is arranged thin for a thin display device 100, the lower surface of the section 111 may have uneven luminance or uneven brightness. For example, regions immediately over the mini-LEDs may appear bright, while regions between the mini-LEDs may appear dim. In order to improve luminance uniformity, more mini-LEDs are added to the array, which increases the assembly and material cost. Further, even when more mini-LEDs are added to the mini-LED array, the diffuser is still needed for providing uniform luminance to the LCD panel.

[0025] Figure 2A schematically shows a cross-sectional view of a display device 200, according to embodiments of the present disclosure. The cross-sectional view is depicted in an X-Z plane. The display device 200 may include a display panel 210, a wavelength conversion unit 211, a backlight module 212, and a diffuser 213. The wavelength conversion unit 211 is adjacent to the display panel 210 and disposed between the display panel 210 and the diffuser 213. The backlight module 212 is disposed proximate to the display module 210 and separated from the display module 210 by the wavelength conversion unit 211, the diffuser 213, and a region 214. The region 214 may be configured between the diffuser 213 and backlight module 212. Optionally, the region 214 may be arranged inside the backlight module 212. In some other cases, the wavelength conversion unit 211, diffuser 213, and a part of the region 214 may be configured inside the display panel 210. As used herein, the terms “unit”, “module”, or “component” have the same meaning or similar meanings and can be used interchangeably.

[0026] The display panel 210 contains a matrix of pixels that form an image by controlling transmission of light through the pixels. Light, as used herein, may also be referred to as light rays. As the display panel 210 does not generate light itself, it needs a backlight such as the backlight module 212. The backlight module 212 emits light to illuminate the pixels of the display panel 210 to create an image. In some embodiments, the display panel 210 may be a LCD panel. In such cases, the display panel 210 may include a liquid crystal layer disposed between an upper substrate and a lower substrate, a first polarization layer, and a second polarization layer. The term “layer”, as used herein, may also indicate a member. The liquid crystal layer is formed of liquid crystal molecules. Transparent electrodes are disposed on the upper and lower substrates. Each pixel of the LCD panel consists of a portion of liquid crystal molecules aligned between an upper and lower transparent electrode. By applying a voltage to a pixel through the electrodes, the arrangement of the liquid crystal molecules of the pixel is changed, and a certain amount of light passes through the pixel and makes the pixel appear a specific level of gray.

[0027] In some cases, the wavelength conversion unit 211 may contain a matrix of color filters deposited on a plate or substrate aligned to the pixels of the LCD panel. As each pixel may have three subpixels corresponding to red, green, and blue color, respectively, three color filters are arranged for a pixel. Color filters may consist of coloring materials such as pigments or dyes for which only light of a certain range of wavelength is transmissive.

[0028] In some other cases, the wavelength conversion unit 211 may contain a matrix of wavelength conversion elements deposited on a plate or substrate. The wavelength conversion elements may absorb light of a shorter wavelength (e.g., light of near ultraviolet), and then emit light of a longer wavelength (e.g., light of red, green, or blue color). Hence, a matrix of wavelength conversion elements may work in a similar way to a matrix of color filters described above.

[0029] The diffuser 213 may contain a diffusion layer made of a diffusion material, and is used to improve luminance uniformity. The display panel 210, wavelength conversion unit 211, and diffuser 213 may be fabricated separately and then bonded together at a later time. Optionally, the diffuser 213 and wavelength conversion unit 211 may be deposited on a plate or substrate sequentially, and the display panel 210 may be subsequently made using the wavelength conversion unit 211 as a base or substrate. Optionally, the display panel 210 may be made first, and the wavelength conversion unit 211 and diffuser 213 may be sequentially deposited on the bottom or lower surface of the display panel 210. In such cases, the diffuser 213 may become the bottom part of the display panel 210. Alternatively, the display panel 210 and wavelength conversion unit 211 may be integrated and made together. For example, a layer containing a matrix of color filters or a matrix of wavelength conversion elements may be configured between two layers of the display panel 210, such as between the liquid crystal layer and the first polarization layer (or the second polarization layer). Then, the wavelength conversion unit 211 may be fabricated between steps of depositing the liquid crystal and first polarization layers.

[0030] The backlight module 212 contains multiple light emitting elements disposed on a substrate. The light emitting elements form a matrix or array with a predetermined grid pattern to illuminate the display panel 210. The light emitting elements may be referred to as light sources, and include lasers, LEDs, micro-LEDs, mini-LEDs, and other small light emitting devices. An LED may also be referred to as an LED chip. A micro-LED chip may have a size smaller than 100 microns. A mini-LED chip may have a size of 100 to 200 microns or 100 to 300 microns. In descriptions below, as an example, a backlight (e.g., the backlight module 212) contains mini-LEDs. Alternatively, a light source may include a light emitting element and a lens that is configured for the light emitting element. That is, a light emitting element and a corresponding lens together may be referred to as a light source.

[0031] The region 214 may include a space between the backlight module 212 and the diffuser 213 or between the mini-LEDs and the diffuser 213. The diffuser 213 and the space (or the region 214) are configured between the wavelength conversion unit 212 (or the display panel 210) and the backlight module 212. When the wavelength conversion unit is a part of the display panel 210, the wavelength conversion unit 211 may be disposed above the mini-LEDs and between a member of the display panel 210 and the substrate of the mini-LEDs. The space in the region 214 may be vacuum or filled with air or an inert gas. In some cases, the space may also be filled with a transparent adhesive material (e.g., transparent resin). As mini-LEDs are small, they may be disposed closer to the diffuser 213 than regular LEDs, and make the region 214 thinner, which may make the display device 200 thinner.

[0032] When mini-LEDs are disposed proximate to the diffuser 213 and display panel 210, the mini-LEDs may irradiate the diffuser 213 with uneven luminance, causing uneven illumination on the display panel 210. While more mini-LEDs may be added to the backlight module 212 to reduce the uneven luminance as used in prior art systems or devices, manufacturing cost would increase. As explained below, the present invention achieves even luminance while not increasing the number of mini-LEDs.

[0033] Figures 2B and 2C schematically illustrate a cross-sectional view 212A and a top view 212B of the backlight module 212 shown in Figure 2A, according to embodiments of the present disclosure. The cross-sectional view 212A is in an X-Z plane, and the top view 212B is in an X-Y plane. As shown in Figures 2B-2C, the backlight module 212 contains mini-LEDs 221, lenses 222, and a substrate 215 on which the mini-LEDs 221 are disposed. The lenses 222 are positioned over the mini-LEDs 221, and aligned with the mini-LEDs 221 in the Z direction, respectively. Please note that the drawings or illustrations of the components/items in the figures (including the lenses) of this application are used for explanation purposes and they do not necessarily represent the actual shapes or dimensions of the components/items. In some embodiments, the mini-LEDs 221 form a matrix or array of light sources with a predetermined grid pattern, and the lenses 222 form a matrix or array of lenses (e.g., as shown in Figure 2C) with the same grid pattern. The quantity, dimension, shape, and arrangement of mini-LEDs and lenses shown in Figures 2B and 2C and in other figures in the present disclosure are exemplary and for description purposes, although any suitable quantity, dimension, shape, and arrangement may be used for the disclosed backlight modules and display devices according to various embodiments of the present disclosure.

[0034] In the backlight module 212, each lens 222 is aligned with a mini-LED 221 along the Z direction or a direction proximately perpendicular to the substrate 215. In some cases, the lenses 222 may be fabricated individually, and then bonded with the mini-LEDs 221 respectively in an assembly process. In some other embodiments, an array of lenses 222 may be formed together by molding. For example, an optical unit or optical component may be molded that contains an array of the lenses 222 with a predetermined pattern. The optical unit may be held over the substrate 215 to make the lenses 222 align with the mini-LEDs 221, respectively. Further, the optical unit may be bonded with the substrate 215 after the alignment is performed.

[0035] The mini-LEDs 221 and lenses 222 are configured such that when light is emitted from the mini-LEDs, the lenses direct light rays or change the propagation direction of the light of each mini-LED differently at different angles. When the intensity of light generated from each mini-LED is changed differently at different angles by the lens 222, the light from the mini-LED array may merge and irradiate the diffuser 213 with relatively uniform luminance. In one aspect, fewer mini-LEDs 221 may be needed for the backlight module 212 and as a result, the manufacturing cost may be reduced. As the backlight module 212 may produce relatively uniform luminance, the diffuser 213 may have higher transmittance than those used in conventional display devices. The efficiency of the display device 200 may be increased. In addition, when the backlight module 212 provides luminance with uniformity beyond a certain level, the diffuser 213 may not be needed. That is, the display device 200 may not contain a diffuser (e.g., the diffuser 213) in some cases, which may lower the manufacturing cost further.

[0036] In descriptions below, lenses (e.g., lenses 222) are designed to create uniform luminance based on a light source array such as a mini-LED array. In some aspect, the mini-LED may be considered as a Lambertian light source that emits light in a Lambertian pattern. Optionally, the mini-LED may be an approximate Lambertian light source. The mini-LEDs are exemplarily used as a Lambertian light source in the following descriptions. As such, when there is no lens, the light from a mini-LED is dispersed according to Lambert's emission law. When a lens is incorporated with a mini-LED, the light emitted from the mini-LED is dispersed according to functions of the lens. The lens, as used herein, may indicate a lens system that contains one or more lenses. A lens may direct light differently at different angles. Since an array of lenses and array of mini-LEDs are used to create uniform luminance, the lens may be designed based on an array of Lambertian light sources and certain values of luminance uniformity on a surface or an interface. The term “interface”, as used herein, indicates a boundary between two regions of space occupied by different materials. A surface may indicate an interface between the air (or vacuum or a gaseous environment) and a solid matter.

[0037] In certain embodiments, when a Lambertian light source irradiates an interface via a lens and values of luminance at each spot on the interface are known, the distribution of light intensity in angular coordinates may be calculated. Based on the distribution of light intensity in the angular coordinates and the radiation pattern of the Lambertian light source, data of the lens may be calculated using, for example, certain methods or lens design software. More details about designing a lens are illustrated below. The term "spot", as used herein, indicate a substantially small region or substantially small area that surrounds a point on an interface.

[0038] Figure 3A schematically shows a top view 300A of a backlight module 300 of a display device (not shown), according to embodiments of the present disclosure. The backlight module 300 contains an array of mini-LEDs 311 with a certain pattern disposed on a substrate 310, while corresponding lenses (or a corresponding array of lenses with the same pattern) are omitted in Figure 3A. The array may exemplarily contain mini-LEDs A to I. The distance between centers of adjacent mini-LEDs 311 along the X direction has a value of a, and the distance between centers of adjacent mini-LEDs 311 along the Y direction has a value of b. In some cases, for example, the value of a and b may be in a range of 3 to 9 millimeters, respectively. Let X2 - X1 = a, X3 – X2 = a, Y2 - Y1 = b, and Y3 – Y2 = b. The values of a and b may be different in some cases. Optionally, the values of a and b may be the same in some other cases.

[0039] Figures 3B and 3C schematically illustrate cross-sectional views 300B and 300C of a structure containing the backlight module 300 shown in Figure 3A, according to embodiments of the present disclosure. The structure may include the backlight module 300 and a diffuser 321 positioned over the lenses 312, mini-LEDs 311, and the backlight module 300. The structure may be a part of the display device and disposed below a display panel (not shown) of the display device. The diffuser 321 has a lower surface or lower interface 322 that faces the lenses

312, the mini-LEDs 311, and the substrate 310. In some cases, assuming that the space between the diffuser 321 and the backlight module 300 is filled with air. Then, the lower interface 322 is an interface between the air and a bottom layer or bottom part of the diffuser 321.

[0040] Figure 3D is a diagram 300D that depicts spots 1 to 9 on the lower interface 322. The diagram 300D shows a view taken against the Z direction, i.e., a direction facing the backlight module 300. Spots 1-9 are immediately over the mini-LEDs A-I, respectively. For example, spot 5, the mini-LED E, and the lens of the mini-LED E are aligned along the Z direction or a direction approximately perpendicular to the substrate 310. As such, spots 1-9 form an array that has the same pattern as that of the array formed by the mini-LEDs 311. Hence, the centers of spots 1-9 are spaced apart by a in the X direction and by b in the Y direction.

[0041] As shown in Figures 3A-3D, the mini-LEDs 311 emit light toward to the diffuser 321 through the lenses 312. If there is no lens and the mini-LEDs irradiate the interface directly, spots 1-9 may be brightly irradiated, while it may be dimly irradiated in regions away from spots 1-9. Thus, the luminance on the lower interface 322 is not uniform. If regular concave lenses are used to further spread light from the mini-LEDs, spots 1-9 may become less brightly irradiated, but the interface may still have uneven luminance with bright areas and dim areas. Consequently, additional mini-LEDs and a diffuser are needed to make the luminance more uniform.

[0042] In the present disclosure, light emitted from a mini-LED 311 is processed by a lens 312. The configuration of the mini-LED array and the function of the lens 312 are arranged such that when all of the mini-LEDs 311 emit light during operation, the luminance uniformity in the area encircled by the mini-LEDs A-D and F-I is above a certain value. Thus, compared to conventional methods, fewer mini-LEDs are employed.

[0043] Figures 3E and 3F schematically show changes of luminance along the X direction and Y direction when a lens 312 is incorporated with the mini-LED E. In Figure 3E, the curve reflects the linear change of luminance along a line L1 that passes through spots 4, 5, and 6 along the X direction with respect to Figure. 3D. In Figure 3F, the curve reflects the linear change of luminance along a line L2 that passes through spots 8, 5, and 2 along the Y direction with respect to Figure. 3D. As shown in Figures 3E-3F, when the mini-LED E is powered on, the luminance is maximum (e.g., an arbitrary value 1) at spot 5, which is immediately over the mini-LED E along the Z direction. In the meantime, the luminance is zero or substantially close to zero (e.g., below a predetermined darkness level) at adjacent spots along the X and Y directions, i.e., spots 2, 4, 6, and 8. The curve shown in Figure 3E follows equations 1A and 1B.

$$E(x) = 1 - (x-X2) / a \quad (1A)$$

$$E(x) = 1 - (X2-x) / a \quad (1B)$$

[0044] Equation 1A applies when x is in a range of X2 to X3 (or “X2+a”), while Equation 1B applies when x is in a range of X1 (or “X2-a”) to X2.

[0045] Similarly, the curve shown in Figure 3F follows equations 2A and 2B.

$$E(y) = 1 - (y-Y2) / b \quad (2A)$$

$$E(y) = 1 - (Y2-y) / b \quad (2B)$$

[0046] Equation 2A applies when y is in a range of Y2 to Y3 (or “Y2+b”), while Equation 2B applies when y is in a range of Y1 (or “Y2-b”) to Y2.

[0047] As above equations describe the linear change, the luminance is half of the maximum value (or substantially close to half of the maximum value) at the midpoint between spots 4 and 5 (or between spots 5 and 6). The midpoint indicates a spot that has an equal distance to spot 4 and spot 5. Hence, along the X direction on the lower interface 322, the luminance in a region at the midpoint between spots 4 and 5 (or between spots 5 and 6) is half or about half of the luminance at spot 5. Similarly, along the Y direction, the luminance in a region at the midpoint between spots 2 and 5 (or between spots 5 and 8) is half or about half of the luminance at spot 5.

[0048] Although the equations 1A, 1B, 2A, and 2B are arranged for spot 5 with regard to the mini-LED E, these equations may be adjusted to fit other spots on the lower interface 322. For irradiation from the mini-LED D and a range of X1 to X2, the luminance on the line L1 follows equation 3.

$$E(x) = 1 - (x - X1) / a \tag{3}$$

[0049] As X2 = X1+a, when the equations 1B and 3 are combined, the total luminance on the line L1 from X1 to X2 is always 1, a constant. In similar manners, when the mini-LEDs G and H are powered on, the luminance on a line connecting spots 7 and 8 is also always 1. When the mini-LEDs C and F are powered on, the luminance on a line connecting spots 3 and 6 is always 1, as well. The constant luminance applies to other lines connecting adjacent spots along the X or Y direction on the lower interface 322.

[0050] When the mini-LED E is on, let the luminance at the spot P (as shown in Figure 3D) follow equation 4, which is based on equations 1B and 2A.

$$E1(x, y) = (1 - (X2 - x) / a) * (1 - (y - Y2) / b) \tag{4}$$

[0051] Similarly, for other light sources proximate and below the spot P, i.e., the mini-LEDs A, B, and D, we have the following equations to express the luminance created at the spot P, respectively.

$$E2(x, y) = (1 - (x - X1) / a) * (1 - (Y3 - y) / b) \tag{5}$$

$$E3(x, y) = (1 - (X2 - x) / a) * (1 - (Y3 - y) / b) \tag{6}$$

$$E4(x, y) = (1 - (x - X1) / a) * (1 - (y - Y2) / b) \tag{7}$$

[0052] When E1(x, y), E2(x, y), E3(x, y), and E4(x, y) are added up, the total value of luminance at any spot on the lower interface is 1 within the range. That is, equations 4 to 7 may be used to express the expected luminance on the lower interface 322 for the mini-LEDs A, B, D, and E when x is in the range of X1 to X2 and y in the range of Y2 to Y3. In similar ways, the luminance on the lower interface 322 generated by the mini-LED E may be calculated and obtained when x is from X1 to X3 and y is from Y1 to Y3. Let the luminance on the lower interface 322 be zero for the mini-LED E when x or y is outside above range.

[0053] In some embodiments, the array of mini-LEDs 311, as shown in Figure 3A, may be considered as an array of a predetermined grid pattern that contains rectangle-shaped lighting units. Each lighting unit includes four light sources disposed at the lighting unit's four corners. The light source contains a mini-LED 311. Optionally, the light source may contain a mini-LED 311 and a lens 312. There are multiple lighting units as shown in Figure 3A. For example, one lighting unit includes the mini-LEDs A, B, D, and E at the four corners, and another lighting unit includes the mini-LEDs B, C, E, and F at the four corners. The lighting unit has a length a along the X direction, and width b along the Y direction. The lighting unit irradiates a corresponding rectangular area with the same grid pattern (e.g., the same length a and width b) on the lower interface. As shown in Figure 3D, a corresponding rectangular area contains spots 1, 2, 4, and 5 at its four corners. A line connecting two spots of the corresponding rectangular area along the X or Y direction may be referred to as a border line. Luminance in the corresponding rectangular area may be arranged using equations depicted above with some adjustment. When the light unit (i.e., four mini-LEDs) is powered on, it irradiates the corresponding rectangular area with luminance uniformity above a certain value. For example, luminance of the corresponding rectangular area including the four border lines may have the same luminance value or substantially similar luminance values. Additionally, when one mini-LED is turned on, it irradiates the corresponding rectangular area in the same manner as described above. For example, when the mini-LED E is on, it irradiates a border line connecting spots 2 and 5 with luminance that changes linearly from a maximum value at spot 5 to zero luminance at spot 2.

[0054] Figure 3G is a schematic diagram showing a light path for the mini-LED E corresponding to the configuration shown in Figure 3B. Assuming that the min-LED E emits light rays that propagate along the light path and impinge on a spot Q on the lower interface 322. The distance between mini-LED E and the lower interface 322 is h. In some cases, for example, the value of h may be in a range of 3 to 6 millimeters. θ is the angle between the light path and the interface normal (i.e., against the Z direction). The distance between the mini-LED E and spot Q is d. Let E be the luminance and I the intensity of light (or light intensity) at spot Q. The luminance and light intensity follow equation 8.

$$E = (I/d^2) * \cos\theta \qquad (8)$$

[0055] Since values of luminance E on the lower interface 322 are known as illustrated above, the light intensity at various spots on the interface 322 may be calculated using equation 8.

[0056] Figures 3H, 3I, 3J, 3K, and 3L are schematic diagrams showing the intensity of light emitted from the mini-LED E with regard to Figures 3A-3D. Arbitrary units are used in these figures. Based on equation 8, the light intensity may be calculated for spots from X2 to X3 along line L1. For each spot on line L1, angle θ may also be calculated. The curve of intensity versus angle along line L1 is shown in Figure 3H. The curve of intensity versus angle from Y2 to Y3 along line L2 is shown in Figure 3I. Figures 3J and 3K schematically depict light distribution curves for all angles. The two curves in Figure 3L also show the intensity versus angle, where one illustrates the change from X1 to X3 along line L1, and the other illustrates the change from Y1 to Y3 along line L2. I_0 is the value of light intensity when the angle is zero.

[0057] After values of light intensity are obtained via calculation, data of a target lens may be obtained by using, for example, certain software including certain lens design software. Data of a lens includes, for example, the shape and dimensions of the incident and exit surfaces, the distance between the incident and exit surfaces, the lens material, the refractive index of the lens material, etc.

[0058] Figure 4 shows a diagram of light passing through an exemplary concave lens 410. The lens 410 has two surfaces 412 and 413 on opposite sides. The surface 412 faces a light source 414 and may be referred to as the light incident surface. The surface 413 faces away from the light source 414 and may be referred to as the light exit surface. Light rays impinge on the incident surface 412 and change the direction of propagation after passing through the incident surface 412 due to refraction. The light rays change the direction of propagation again after passing through the exit surface when exiting the lens 411 due to refraction.

[0059] Designing a lens involves determining the incident surface and the exit surface of the lens. In some cases, the incident surface may be determined first at the beginning of a lens design process to reduce the calculation load. The predetermined incident surface may include, for example, a flat surface or a curved surface (e.g., a convex surface, a concave surface, an aspheric surface, or a freeform surface). The term “free form surface”, as used herein, indicates a surface that has no rotational symmetry or translation around the optical axis. As both the incident and exit surfaces are used to change the propagation direction of light rays, it may be arranged that one of them makes a bigger change of propagation direction than the other one. For example, in some cases, about 50-70% of the change of propagation direction may be made by the exit surface.

[0060] Figure 5 is a diagram illustrating light rays irradiating a surface after passing through a lens, and used to describe a lens design process schematically. Assuming that a light source 511 is disposed at a location under a lens. The lens has an incident surface 512 and exit surface 513. The light source 511 generates light rays that pass through the lens and then illuminate a flat surface 514 (e.g., the bottom surface of a diffuser). Assuming that the surface 514 receives all light emitted from the light source 511. Based on energy conservation, equation 9 is obtained.

$$\iint I(u,v)dudv = \iint E(x,y)dxdy \qquad (9)$$

[0061] I(u,v) represents the light intensity emitted by the light source 511 in an angular coordinate system (u,v). E(x,y) represents the luminance received on the surface 514 in a Cartesian coordinate system (or orthogonal coordinate system) (x,y). From equation 9, equations 10 and 11 are obtained.

$$\iint I_0 \cos u * \cos^2 v \, dudv = \iint E(x,y)dxdy \qquad (10)$$

$$I_0 \cos u * \cos^2 v \, dudv = E(x,y)dxdy \qquad (11)$$

[0062] I_0 is a fixed value determined by prearranged conditions. Equation 11 illustrates energy conservation in a differential form, i.e., the luminance received in a small area at (x,y) on the surface 514 corresponds to the light intensity of a small portion of light rays at (u,v).

[0063] When light passes through the incident surface 512 and exit surface 513 sequentially, it is refracted twice. The refracted angle follows Snell's law of refraction. As such, the optical path of each light ray, from the light source 511 to the surface 514 via the lens, may be calculated using Snell's law.

[0064] When the radiation pattern (e.g., light intensity at different angles) of the light source 511 and desired values of luminance on the surface 514 are known, the shape of the incident and exit surfaces 512 and 513 and other data of the lens may be obtained by calculation. As illustrated above, the desired values of luminance on the surface 514 may be obtained using equations 1A, 1B, 2A, 2B, and 4 with some adjustment. The desired values of luminance may also be referred to as the expected values of luminance. In some cases, the incident surface 512 may be predetermined and thus has a known surface with fixed data. The exit surface 513 is a free form surface and may have certain predetermined initial data. For example, the exit surface 513 may have an initial shape that will be adjusted or modified multiple times during the lens design process.

[0065] As radiation patterns of the light source 511 and data of the incident surface 512 are known, after light rays pass through the incident surface 512, a calculation process may be performed to determine optical paths or trajectories of the light rays inside the lens as a result of diffraction. The light rays may be divided into small portions and the trajectory of each small portion inside the lens is calculated. The exit surface 513 may be divided into small regions. Each small portion of the light rays may impinge onto one or more small regions of the exit surface 513. The surface 514 may be divided into small areas. As the trajectory of each small portion of the light rays may be calculated after the light rays exit the lens, and each trajectory leads to one or more of the small areas of the surface 514, the location of corresponding small area or small areas of the surface 514 may be obtained. Subsequently, luminance in the corresponding small area or small areas may be calculated using equation 11 when the light rays impinge onto the surface 514.

[0066] The calculated values of luminance on the surface 514 are compared with the expected values of luminance, and the difference between them is used to adjust the data of the exit surface 513. For example, if the luminance value is too big in a small area of the surface 514, one or more corresponding small regions of the exit surface 513 may be identified. Thereafter, the one or more corresponding small regions of the exit surface 513 may be adjusted to steer some part of the one or more corresponding small portions of light rays away from the one or more corresponding small areas of the surface 514. The method may be performed to adjust every small regions of the exit surface 513, and above steps may repeat multiple times until the difference between the calculated values of luminance and expected values of luminance on the surface 514 is below a certain level. Then, the finalized small regions of the exit surface 513 are stitched together to form the exit surface 513.

[0067] Referring to Figures 3A-3D, when the mini-LED E is on, the luminance on the lower interface 322 may be determined by equations 1A, 1B, 2A, 2B, and 4. In some other embodiments, when the mini-LED E is on, the luminance on the lower interface 322 may also be determined by equations 12A-12D and 13A, which represents other optional methods to generate even luminance.

$$E\ (x) = 1 - \frac{1}{1+e^{k(x-X2-\frac{a}{2})}} \tag{12A}$$

$$E\ (x) = 1 - \frac{1}{1+e^{k(X1+\frac{a}{2}-x)}} \tag{12B}$$

$$E\ (y) = 1 - \frac{1}{1+e^{k(y-Y2-\frac{a}{2})}} \tag{12C}$$

$$E\ (y) = 1 - \frac{1}{1+e^{k(Y1+\frac{a}{2}-y)}} \tag{12D}$$

$$E1\ (x, y) = \left(1 - \frac{1}{1+e^{k(X1+\frac{a}{2}-x)}}\right) * \left(1 - \frac{1}{1+e^{k(y-Y2-\frac{a}{2})}}\right) \tag{13A}$$

[0068] In above equations, k is a predetermined coefficient. Equation 12A applies when x is in a range of X2 to X3 (or "X2+a"), while equation 12B applies when x is in a range of X1 (or "X2-a") to X2. Equation 12C applies when y is in a range of Y2 to Y3 (or "Y2+b"), while equation 12D applies when y is in a range of Y1 (or "Y2-b") to Y2. Equation 13A applies when x is in the range of X1 (or "X2-a") to X2 and y is in the range of Y2 to Y3 (or "Y2+b"). Equation 13A may be used to determine the luminance at spot P.

[0069] Figures 6A and 6B schematically show changes of luminance along lines L1 and L2 (with respect to Figure 3D) based on equations 12A-12D when the mini-LED E is on. In Figure 6A, the curves S1, S2, and S3 reflect the change of luminance along line L1 when the values of k are -1.6, -0.5, and -100, respectively. The values of k is arbitrary and for illustrating the change of luminance in different scenarios only. In Figure 6B, the curves S4, S5, and S6 reflect the change of luminance along line L2 when the values of k are -1.6, -0.5, and -100, respectively. Based on equations 12A-12D and Figures 6A-6B, the luminance has the maximum value at spot 5 along each curve. The maximum luminance may be close to 1 (i.e., an arbitrary value) or substantially close to 1 in some cases. The luminance has minimum values at spots 2, 4, 6, and 8 on the curves. The minimum luminance may be close to 0 (or below a predetermined darkness level) or substantially close to 0 in certain cases. The luminance has a constant value of 0.5 at the midpoints between spots 4 and 5, 5 and 6, 2 and 5, and 5 and 8, respectively. As illustrated above, the midpoints indicate spots that are halfway between spots 4 and 5, 5 and 6, 2 and 5, and 5 and 8, respectively. For a point (or spot) between spot 5 and a midpoint, the luminance value is between 0.5 and the maximum value based on the equations. For a point (or spot) between spot 4 and the corresponding midpoint between spots 4 and 5, the luminance value is between 0.5 and the minimum value based on equation 12B. Additionally, for a point between spots 4 and 5, the luminance value is between the maximum and minimum values based on equation 12B, i.e., based on a change of luminance value from the maximum to the minimum according to a function defined by equation 12B. Assuming that for spots located outside the range on the lower interface 322, the luminance created by the mini-LED E is zero.

[0070] Further, when the mini-LEDs D and E are powered on, the total luminance on line L1 from X1 to X2 is always 1 based on equations 12A and 12B. When the mini-LEDs E and F are powered on, the total luminance on line L1 from X2 to X3 is always 1 based on equations 12A and 12B. When the mini-LEDs B and E are powered on, the total luminance on line L2 from Y2 to Y3 is always 1 based on equations 12C and 12D. When the mini-LEDs E and H are powered on, the total luminance on line L2 from Y1 to Y2 is always 1 based on equations 12C and 12D. The constant luminance applies to other lines connecting adjacent spots along the X or Y direction on the lower interface 322, when two corresponding adjacent mini-LEDs are turned on.

[0071] Based on the descriptions above, the total luminance along line L1 from spot 4 to spot 5 is always 1 when the mini-LEDs D and E are powered on. When the mini-LED E is powered on, the luminance has a maximum value at spot 5, a minimum value at spot 4, and a constant value of 0.5 at the midpoint between spots 4 and 5. When the mini-LED D is powered on, the luminance has a maximum value at spot 4, a minimum value at spot 5, and a constant value of 0.5 at the midpoint between spots 4 and 5. Assuming that the mini-LEDs D and E (or A to I) have the same structure and characteristics, and thus have the same or substantially close maximum luminance values and the same or substantially close minimum luminance values along line L1 from X1 to X2. As such, when the mini-LED D or E is powered on, the value of luminance at the midpoint between spots 4 and 5 is half of the addition of the maximum value and the minimum value or a value substantially close to half of the addition. For example, when the mini-LED E is powered on, the luminance has a maximum value at spot 5 and a minimum value at spot 4. The addition of the maximum and minimum values is 1 and the value of luminance at the midpoint between spots 4 and 5 is 0.5, i.e., half of the addition of the maximum and minimum values.

[0072] In addition, the luminance produced by the mini-LEDs A, B, or D may be determined in the same manner as that by the mini-LED E. The following equations are arranged for the mini-LEDs A, B, and D, respectively, when x is in the range of X1 (or "X2-a") to X2 and y in the range of Y2 to Y3 (or "Y2+b").

$$E2\ (x, y) = (1 - \frac{1}{1+e^{k(x-X1-\frac{a}{2})}}) * (1 - \frac{1}{1+e^{k(Y2+\frac{a}{2}-y)}}) \qquad (13B)$$

$$E3\ (x, y) = (1 - \frac{1}{1+e^{k(X1+\frac{a}{2}-x)}}) * (1 - \frac{1}{1+e^{k(Y2+\frac{a}{2}-y)}}) \qquad (13C)$$

$$E4\ (x, y) = (1 - \frac{1}{1+e^{k(x-X1-\frac{a}{2})}}) * (1 - \frac{1}{1+e^{k(y-Y2-\frac{a}{2})}}) \qquad (13D)$$

[0073] When equations 13A-13D are added up, we have the addition of E1(x, y), E2(x, y), E3(x, y), and E4(x, y), i.e., the total value of luminance at any spot on the lower interface within the range. The total value of luminance is always 1 based on the equations, reflecting a case of ideal uniform luminance. As such, equations 13A-13D may be used to express the expected luminance on the lower interface 322 for the mini-LEDs E, A, B, and D, respectively, when x is in the range of X1 to X2 and y in the range of Y2 to Y3. With similar methods, the luminance produced by the mini-LED E, A, B, or D in other regions on the lower interface 322 may be determined as well.

[0074] Therefore, the luminance on the lower interface 322 may be determined or described by equations 12A-12D, 13A-13D, and equations that are based on equations 12A-12D and 13A-13D.

As such, equations 12A-12D and 13A-13D, especially equations 12A-12D and 13A, may be utilized to design a lens for achieving uniform luminance in similar ways to that illustrated above when equations 1A, 1B, 2A, 2B, and 4 are used.

[0075] Figures 7A and 7B schematically show configurations 700A and 700B of the light sources, according to embodiments of the present disclosure. As described above, light sources (e.g., mini-LEDs) may be arranged based on the light units. The light units have a rectangular or square shape. Referring to the configuration 700A of Figure 7A, in some embodiments, the lighting unit, depicted in dashed lines, may include four light sources disposed at the lighting unit's four corners. The lighting unit may have a length c along the X direction, and width d along the Y direction. The lighting unit is configured to irradiate a corresponding rectangular area (not shown) with the same grid pattern (e.g., the same length c and width d) on an interface. The total area of even luminance on the interface may equal to the total area of the lighting units of the configuration 700A.

[0076] Referring to the configuration 700B of Figure 7B, in some other embodiments, the lighting unit, depicted in dashed lines, may have a light source disposed at the center of the lighting unit. The lighting unit may have a length c along the X direction, and width d along the Y direction. Accordingly, the light sources form the same grid pattern with a length c along the X direction, and width d along the Y direction. The lighting unit may be configured to irradiate a corresponding rectangular area (not shown) with the same grid pattern (e.g., the same length c and width d) on an interface. The total area of even luminance on the interface may be smaller than the total area of the lighting units of the configuration 700B, since certain edge regions of the corresponding rectangular areas are relatively dimly irradiated by one light source only. These edge regions have lower luminance and are excluded from areas of even luminance.

[0077] Figure 8 shows a flow chart 800 for designing a lens for a backlight module, according to embodiments of the present disclosure. At step 811, data of a light source array is obtained. The data of the array may include pitches of the array along the X and Y directions that determine the distance between adjacent light sources along the X and Y directions. The light sources are disposed at the grid points of the array.

[0078] At step 812, a distance between a substrate and an illumination interface is obtained. The distance and data of the light source array are initial conditions for designing the lens. The light sources are disposed on a substrate, and the illumination interface may be a bottom surface of a diffuser that is away from the substrate with a predetermined distance. In some cases when the diffuser is inside or integrated with a display panel, the illumination interface may be disposed inside the display panel. That is, the illumination interface may be configured between the substrate and a layer (or member) of the display panel.

[0079] At step 813, values of luminance on the illumination interface, as part of the initial conditions, are obtained by calculation and used as the expected values of luminance. The distance between adjacent light sources along the X and Y directions, and the distance between the substrate and illumination interface are used in the calculation. In some cases, equations such as equations 1A, 1B, 2A, 2B, and 4 (or equations 12A-12D and 13A) may be used to acquire the expected values of luminance.

[0080] At step 814, values of luminance on the illumination interface are calculated based on the above-described method. For example, equation 11, Snell's law, predetermined data of the lens including data of the incident surface, and temporary data of the exit surface of the lens may be used in the calculation.

[0081] At step 815, the calculated values of luminance on the illumination interface are compared with the expected values of luminance. The exit surface may be divided into small regions. Based on the comparison results, each small region of the exit surface is adjusted individually. Thereafter, steps 814 and 815 may be repeated to calculate values of luminance on the illumination interface based on the adjusted data of the exit surface, and compare the calculated values of luminance with the expected values of luminance. When the difference between the calculated values of luminance with the expected values of luminance is below a certain level, data of the exit surface or data of the lens is finalized at step 816.

[0082] Data of the lens may include data of the incident and exit surfaces, lens dimensions, refractive index of the lens material, and other characteristics. Without the lens, the light source emits light according to its original radiation pattern. For example, a mini-LED may emit light in a nearly Lambertian pattern. When the lens is coupled to the light source, the lens directs the light from the light source to irradiate the illumination interface. Light intensity is changed from an original radiation pattern to a modified pattern. Besides methods illustrated above, certain lens design software, which has been available in the field for some time, may be used to design the lens with the initial conditions. In some cases, the original radiation pattern of a light source may be measured and analyzed first. In some cases, as illustrated above, the incident surface of a lens may be predetermined as an initial condition to simplify the calculation process. Alternatively, both the incident and exit surfaces of a lens may be calculated, adjusted, and finalized at the same time.

[0083] Steps 811-816 describe methods to design a lens that may be used to improve luminance uniformity for a display device. The display device may contain a mini-LED array, a lens array, and a display panel. The mini-LED array and lens array are incorporated to illuminate the display panel with uniform luminance. Further, the mini-LED array and lens array may be scaled with the same grid pattern. For example, more mini-LEDs 311 and lenses 312 may be added to the arrays shown in Figures 3A-3C to expand the arrays. As such, the mini-LED array and lens array may be used for display devices of small sizes and large sizes conveniently. In addition, the mini-LED array and lens array may also be used for other devices or in other applications that need uniform luminance.

[0084] After the lens design process, data of the lens is recorded and transferred to a manufacturing facility. A number of the lenses may be made for constructing a lens array. Optionally, the lenses may be fabricated in the form of lens array. That is, a lens array arranged for a backlight module or display device may be prefabricated by, for example, a molding method before an assembly process.

[0085] Figure 9 shows a flow chart 900 for fabricating a backlight module and a display device, according to embodiments of the present disclosure. A substrate is provided at step 911 for assembling a backlight module. The substrate may be a semiconductor substrate including a semiconductor material, or an insulating substrate including an electrically non-conductive material such as glass, a plastic material, or a ceramic material. Optionally, the substrate may also be a printed circuit board (PCB).

[0086] At step 912, light sources (e.g., mini-LEDs) are mounted on the substrate to form a light source array with a predetermined pattern (e.g., with predetermined pitch values along the X and Y directions). In some embodiments, the light sources are bonded on the substrate with an adhesive material after an alignment step is performed.

[0087] At step 913, lenses designed for the backlight module are provided. Each lens is disposed over and aligned with a light source on the substrate, and then fixed by, for example, a bonding method using an adhesive material and optionally, a lens fixture. In some embodiments, a lens array is prefabricated. The lens array may be placed over and aligned with the light source array in a direction approximately perpendicular to the substrate, and then get bonded using an adhesive material and optionally, a lens array fixture. In some embodiments, a housing unit may be provided for the backlight module. The housing unit may accommodate the substrate, light source array, and lens array. Optionally, the substrate may be disposed in the housing unit before the light sources are mounted.

[0088] At step 914, a diffuser and a wavelength conversion unit are disposed over the lens array or the backlight module sequentially. The diffuser may be placed at a predetermined distance from the light source array or the substrate, aligned to the lens array or the light source array in a direction approximately perpendicular to the substrate, and then bonded using an adhesive material. In some cases, the diffuser may be bonded with the housing unit. Further, the wavelength conversion unit may be placed above the diffuser, aligned to the lens array or the light source array in a direction approximately perpendicular to the substrate, and then bonded using an adhesive material. In some cases, the wavelength conversion unit may be bonded with the housing unit.

[0089] At step 915, a display panel is disposed over the wavelength conversion unit, aligned with the wavelength conversion unit in a direction approximately perpendicular to the substrate, and bonded with it. Optionally, the display panel may also be aligned with the substrate during the assembly process. For example, certain marks may be made on the substrate for alignment purpose. In some cases, the display panel may be bonded with the housing unit. In some embodiments, the housing unit may be designed to accommodate and protect all components of the display device including the backlight module and display panel.

[0090] Steps 911-913 describe methods and processes to fabricate a backlight module. In some cases, backlight modules may be made separately at a facility, and then sent to another facility for assembly of display devices. Alternatively, a display device may be fabricated through consecutive steps starting from mounting light sources on a substrate (e.g., steps 911-912). The steps further include disposing a lens array over the light source array, a diffuser over the lens array, a wavelength conversion unit over the diffuser, and a display panel over the wavelength conversion unit.

[0091] Optionally, a display panel may contain a diffuser and a wavelength conversion unit. In such cases, the steps of disposing a diffuser and a wavelength conversion unit over a backlight module as described above may be omitted. The backlight module and display panel may be aligned and bonded to form a display device directly.

[0092] In some other embodiments, a display device may not contain a diffuser. Consequently, above-described methods may omit the step of mounting a diffuser (e.g., aligning and bonding a diffuser). A wavelength conversion unit may be configured over a lens array directly. That is, a wavelength conversion unit may be positioned over and aligned with a lens array directly in an assembly process of display devices.

[0093] Figure 10 is an exemplary structural diagram 1000 of a display device. The display device may include a display panel 1011, a wavelength conversion unit (not shown), a backlight module 1012, and a controller 1013. The display panel 1011 may be a LCD panel. The backlight module 1012 may include a mini-LED array and provide uniform luminance for the wavelength conversion unit via a lens array. The controller 1013 may include a first control circuit that sends control signals to a gate driving circuit (not shown) and a data driving circuit (not shown). The gate driving circuit and data driving circuit are arranged to drive the display panel 1011 during operation of the display device. For example, the gate driving circuit may output scan signals, and the data driving circuit may output data voltage. The controller 1013 may further include a second control circuit that controls the backlight module 1012. The controller 1013 may be mounted on a PCB that is attached to a housing unit of the display device. The display device may also contain a power supply circuit (not shown) that supplies and controls various voltages or currents to the display panel 1011, the first and second control circuits, the gate driving circuit, the data driving circuit, and the backlight module (i.e., the mini-LEDs).

[0094] Although specific embodiments of the invention have been disclosed, those having ordinary skill in the art will understand that changes can be made to the specific embodiments without departing from the spirit and scope of the invention. The scope of the invention is not to be restricted, therefore, to the specific embodiments. Furthermore, it is intended that the appended claims cover any and all such applications, modifications, and embodiments within the scope of the present invention.

We claim:

CLAIMS:

1. A backlight module for a display device, comprising:

a substrate and a plurality of LED light sources disposed on the substrate following a grid pattern to form a plurality of rectangle-shaped lighting units,

wherein each lighting unit comprises four LED light sources disposed at the lighting unit's four corners, respectively, has a length L along a first direction X and a width W along a second direction Y, and irradiates a corresponding rectangular area with the same length L and width W on an interface of the display device,

wherein each LED light source comprises an LED and a corresponding lens disposed above the LED, the corresponding lens directing light rays emitted from the LED onto

(1) a first corner of the corresponding rectangular area on the interface of the display device with a first luminance value E1,

(2) a second corner of the corresponding rectangular area with luminance of a first predetermined value, wherein a distance between the first corner and the second corner is L along the X direction,

(3) a first location (x, 0) with a luminance value E (x, 0) that is determined based on a change of luminance value from the first luminance value E1 at the first corner to the first predetermined value at the second corner, wherein the first location is on a first border line between the first corner and the second corner, and x is a distance between the first location (x, 0) and the first corner along the X direction,

(4) a third corner of the corresponding rectangular area with luminance of a second predetermined value, wherein a distance between the first corner and the third corner is W along the Y direction,

(5) a second location (0, y) with a luminance value E (0, y) that is determined based on a change of luminance value from the first luminance value E1 at the first corner to the second predetermined value at the third corner, wherein the second location is on a second border line between the first corner and the third corner, and y is a distance between the second location (0, y) and the first corner along the Y direction, and

(6) a third location (x, y) of the corresponding rectangular area with a luminance value of E (x, y) that is a product of E (x, 0) and E (0, y).

2. The backlight module of claim 1, wherein the LED is a mini light emitting diode (mini-LED).

3. The backlight module of claim 1, wherein the LED has a dimension smaller than 300 micrometers along the X direction or Y direction.

4. The backlight module of claim 1, wherein luminance uniformity in the corresponding rectangular area on the interface of the display device is beyond a predetermined value when the four LED light sources at the lighting unit's four corners irradiate the corresponding rectangular area.

5. The backlight module of claim 1, wherein the display device has a liquid crystal display (LCD) panel.

6. The backlight module of claim 1, wherein corresponding lenses of the plurality of LED light sources form an array of lenses with the grid pattern.

7. The backlight module of claim 6, wherein the array of lenses is made by molding.

8. The backlight module of claim 1, wherein the change of luminance value from the first luminance value E1 at the first corner to the first predetermined value at the second corner is determined by a predetermined function.

9. The backlight module of claim 1, wherein the length L and width W are smaller than 9 millimeters, respectively.

10. The backlight module of claim 1, wherein a distance between the interface and the substrate is smaller than 6 millimeters.

11. A backlight module, comprising:

a substrate;

a first light source, disposed on the substrate;

a second light source, disposed on the substrate and adjacent to the first light source;

a first lens; and

a second lens,

wherein the first light source, the first lens, and a first spot are aligned along a direction approximately perpendicular to the substrate, the second light source, the second lens, and a second spot are aligned along the direction, light emitted from the first light source passes through the first lens to irradiate the first spot with luminance of a first value, irradiate the second spot with luminance of a second value, and irradiate a middle spot with luminance of a value that is half of addition of the first and second values or substantially close to half of addition of the first and second values, and the middle spot is between the first spot and the second spot.

12. The backlight module of claim 11, wherein light emitted from the second light source passes through the second lens to irradiate the second spot with luminance of a third value, irradiate the first spot with luminance of a fourth value, and irradiate the middle spot with

luminance of a value that is half of addition of the third and fourth values or substantially close to half of addition of the third and fourth values.

13. The backlight module of claim 12, wherein the first value and third value are substantially close and/or the second value and fourth value are substantially close.

14. The backlight module of claim 11, wherein the middle spot is a midpoint between the first spot and second spot.

15. The backlight module of claim 11, wherein the second value is below a predetermined darkness level.

16. The backlight module of claim 12, wherein the fourth value is below a predetermined darkness level.

17. The backlight module of claim 11, wherein the first and second light sources include mini light emitting diodes (mini-LEDs).

18. The backlight module of claim 11 further comprises additional light sources and additional lenses, the first and second light sources and the additional light sources forming an array of light sources of a predetermined grid pattern, and the first and second lenses and the additional lenses forming an array of lenses of the predetermined grid pattern.

19. The backlight module of claim 18, wherein the array of lenses is made by a molding method.

20. The backlight module of claim 11, wherein a distance between the first spot and the substrate is smaller than 6 millimeters.

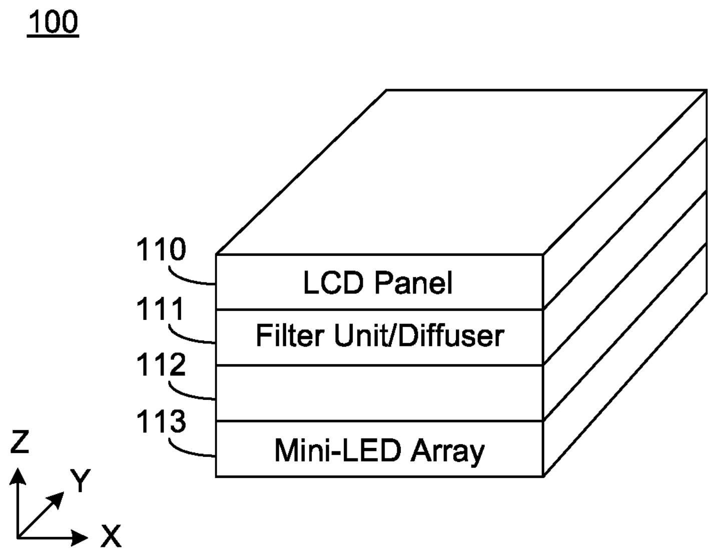

FIG. 1 (Prior Art)

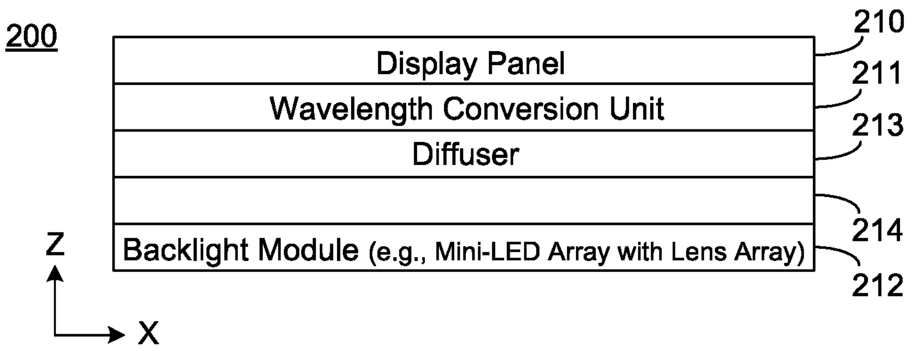

FIG. 2A

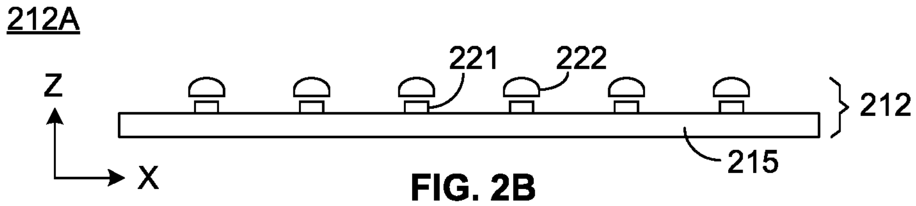

FIG. 2B

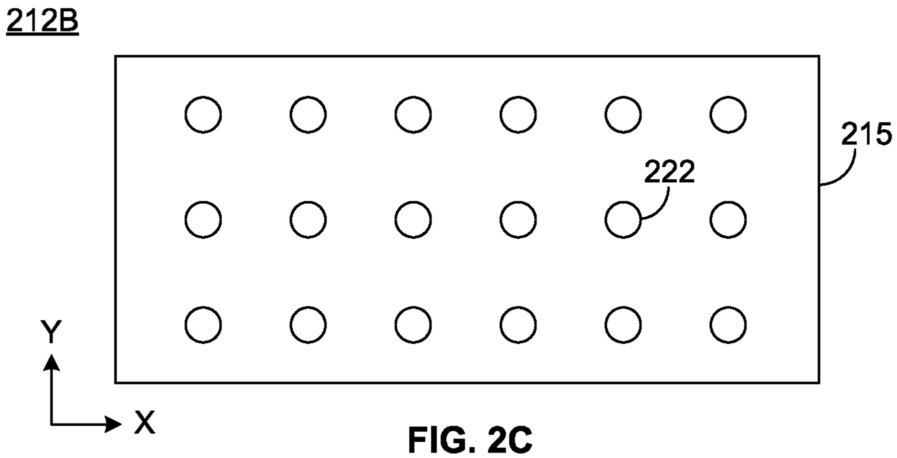

FIG. 2C

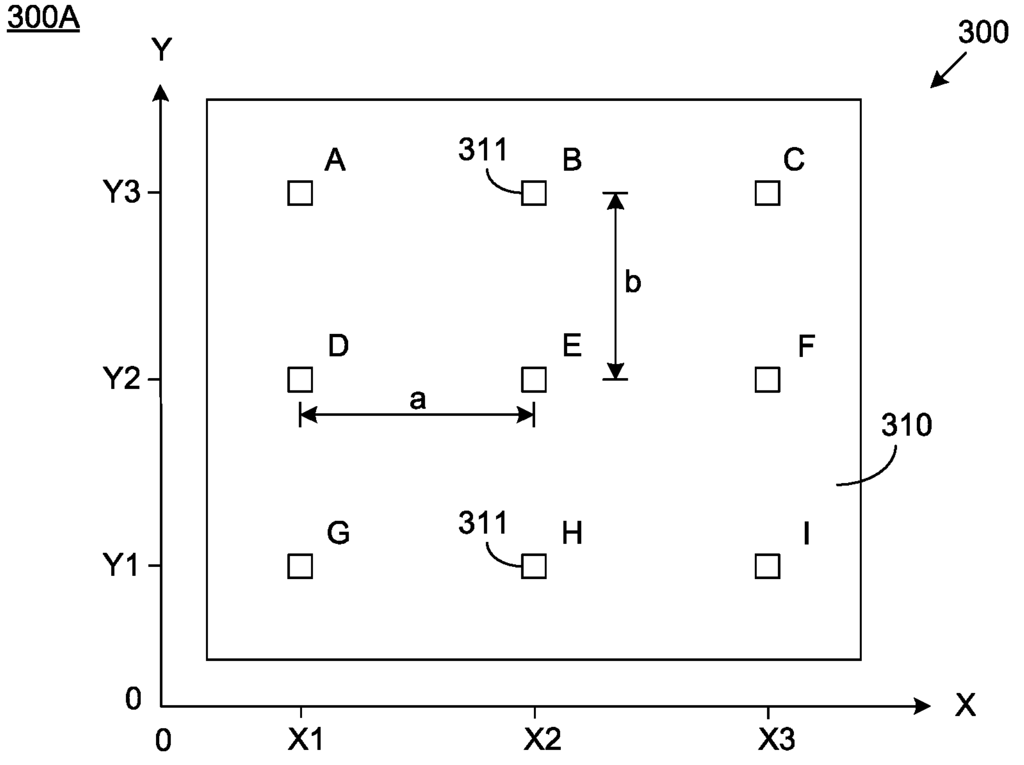

FIG. 3A

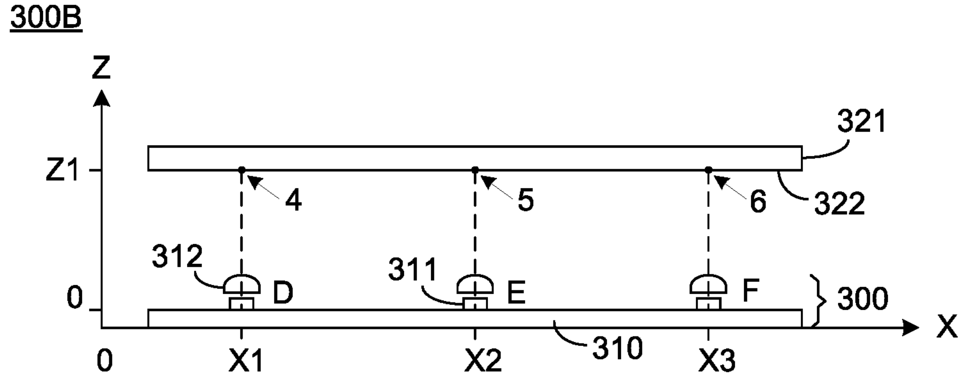

FIG. 3B

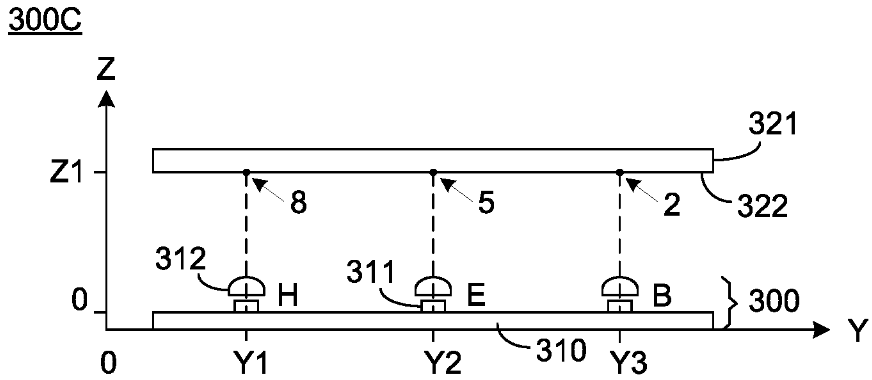

FIG. 3C

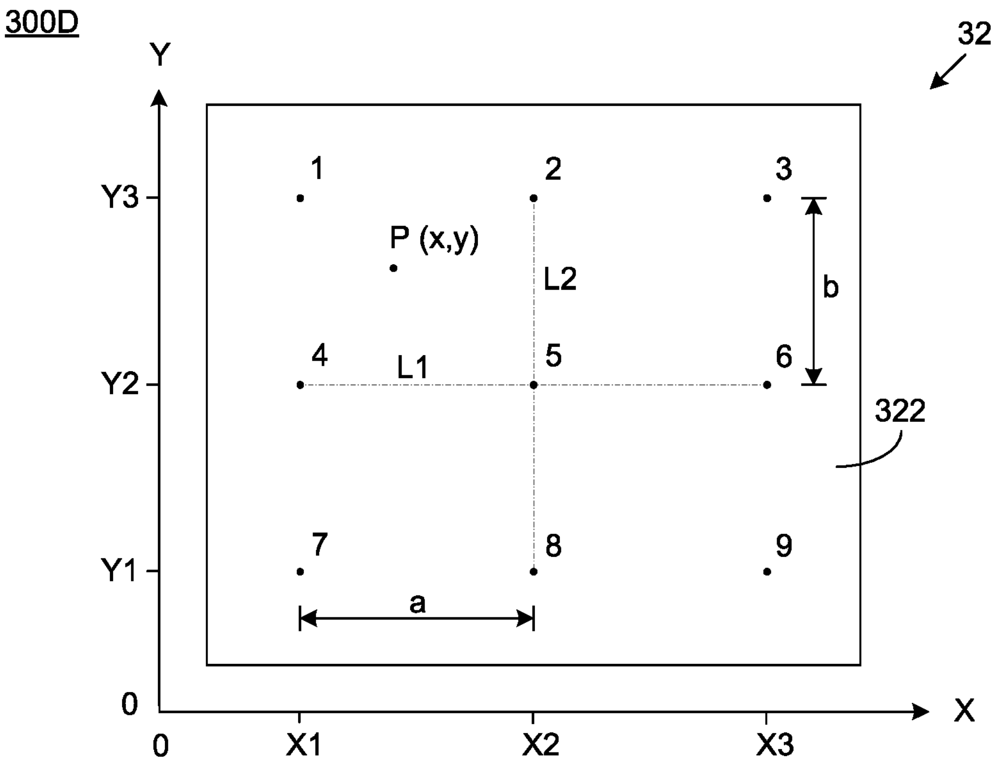

FIG. 3D

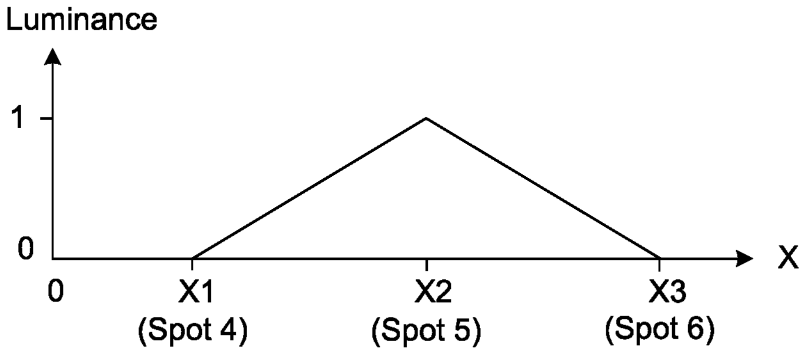

FIG. 3E

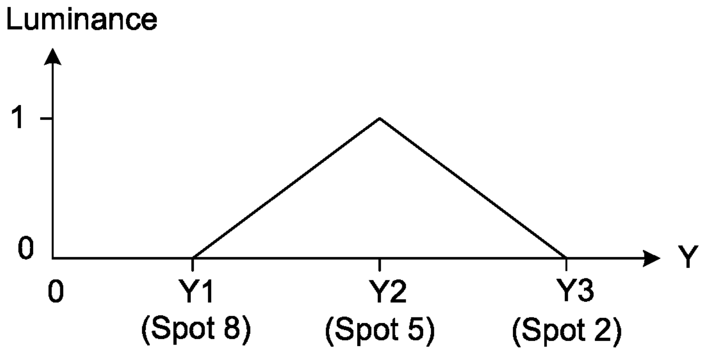

FIG. 3F

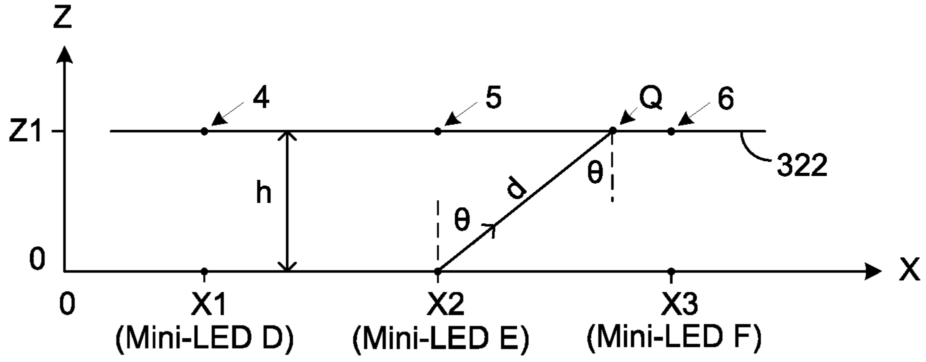

FIG. 3G

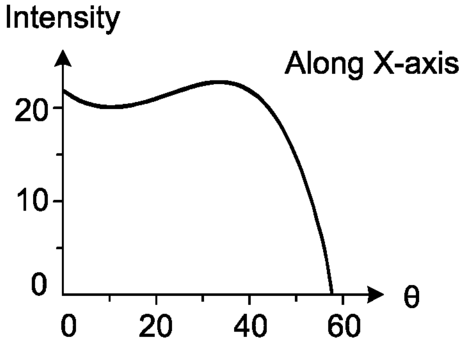

FIG. 3H

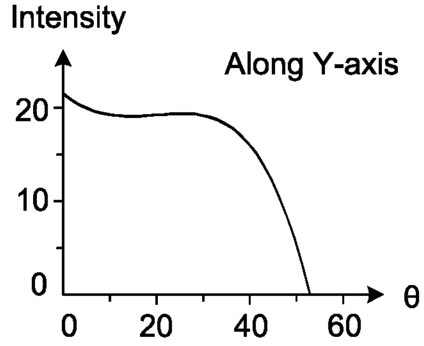

FIG. 3I

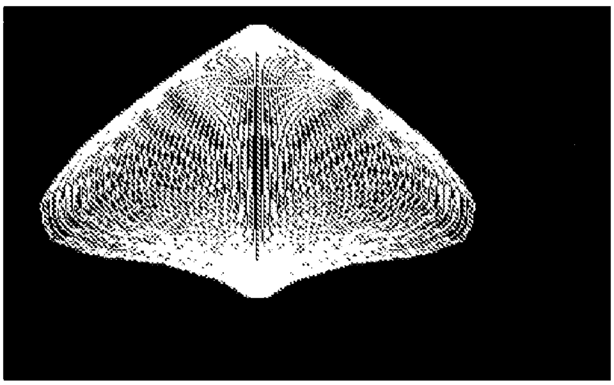

FIG. 3J

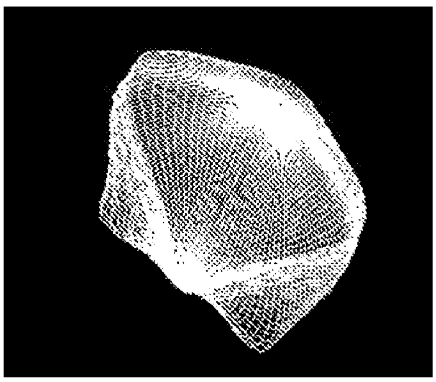

FIG. 3K

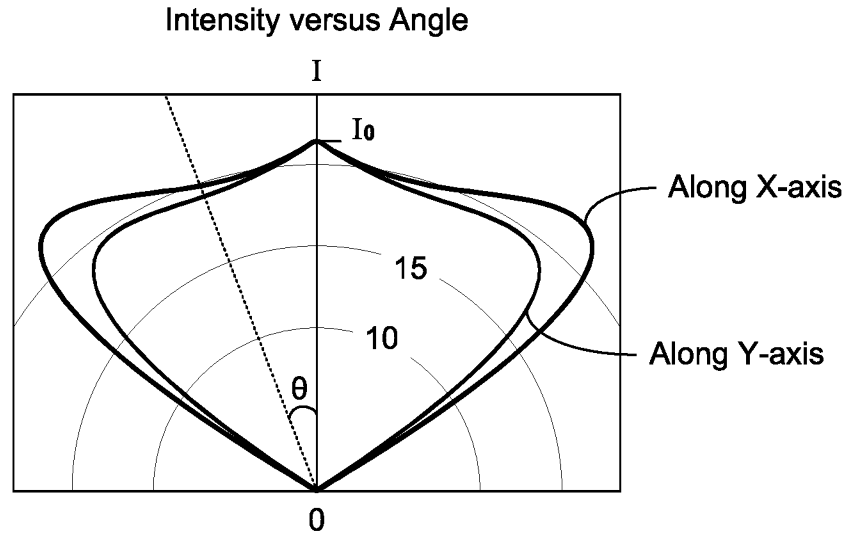

FIG. 3L

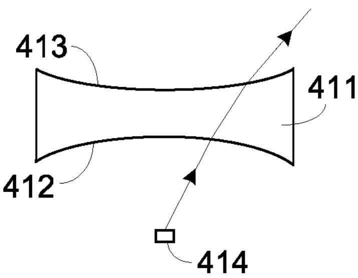

FIG. 4

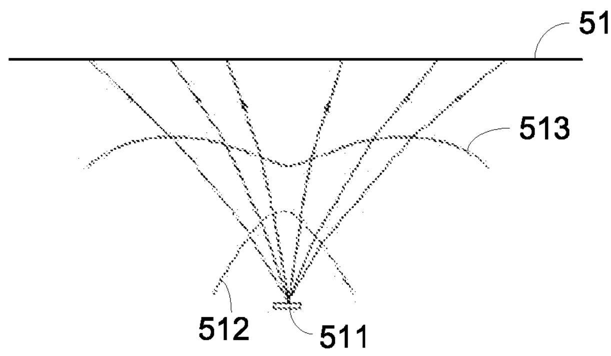

FIG. 5

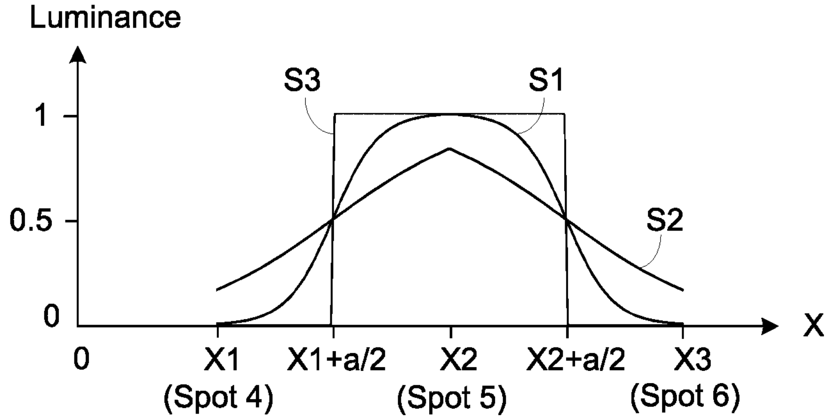

FIG. 6A

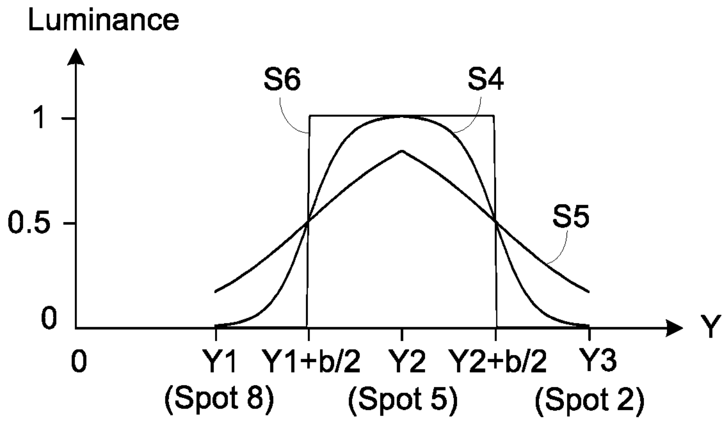

FIG. 6B

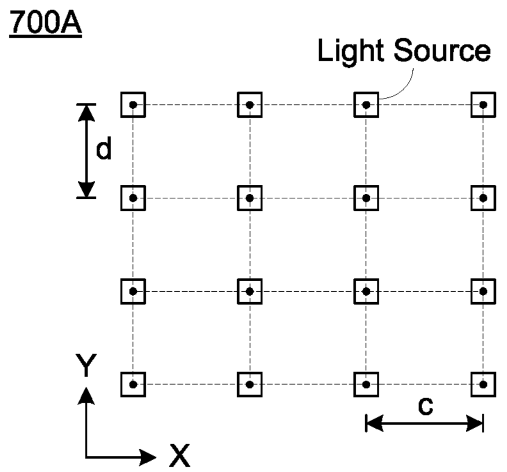

FIG. 7A

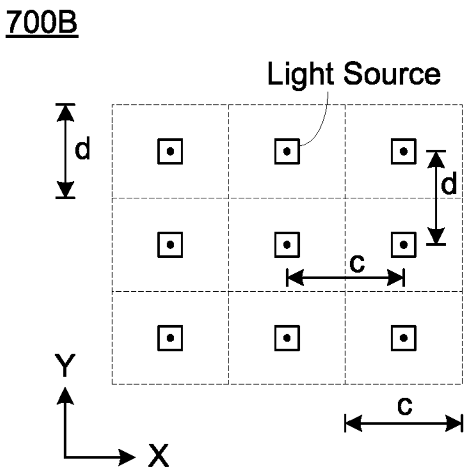

FIG. 7B

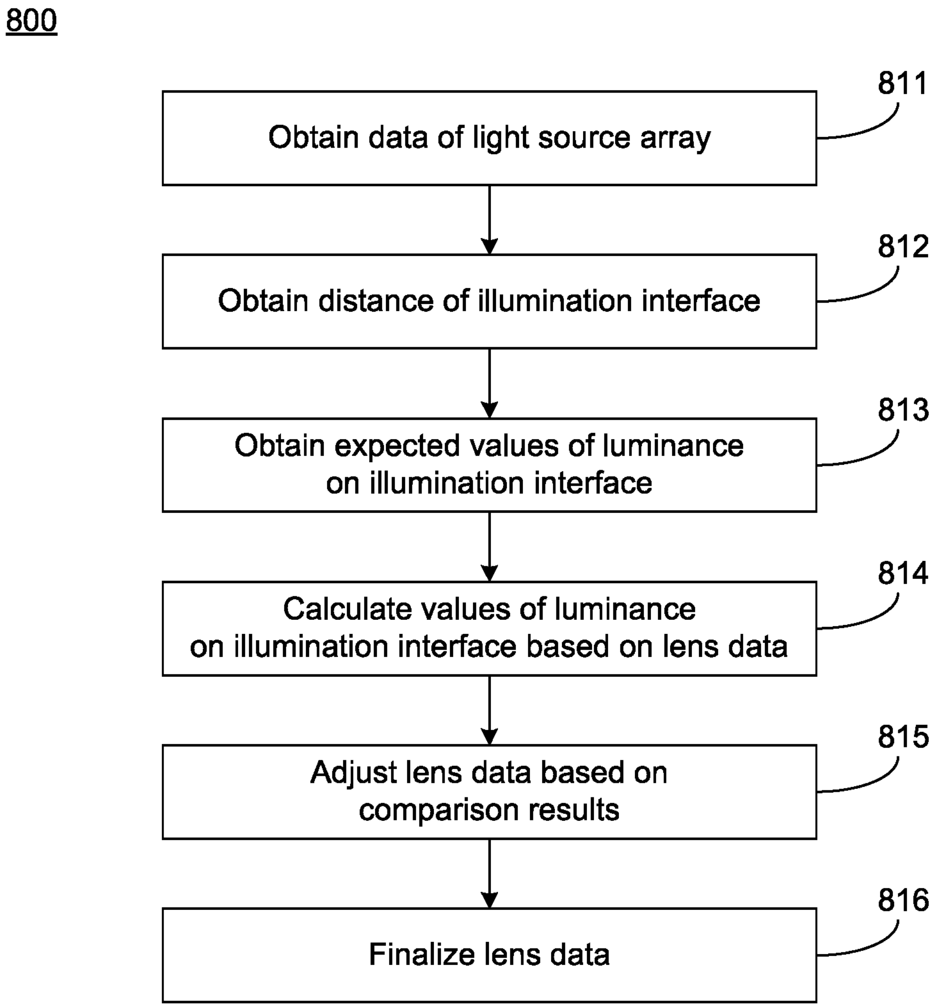
800
Obtain data of light source array
811
Obtain distance of illumination interface
812
Obtain expected values of luminance on illumination interface
813
Calculate values of luminance on illumination interface based on lens data
814
Adjust lens data based on comparison results
815
Finalize lens data
816

FIG. 8

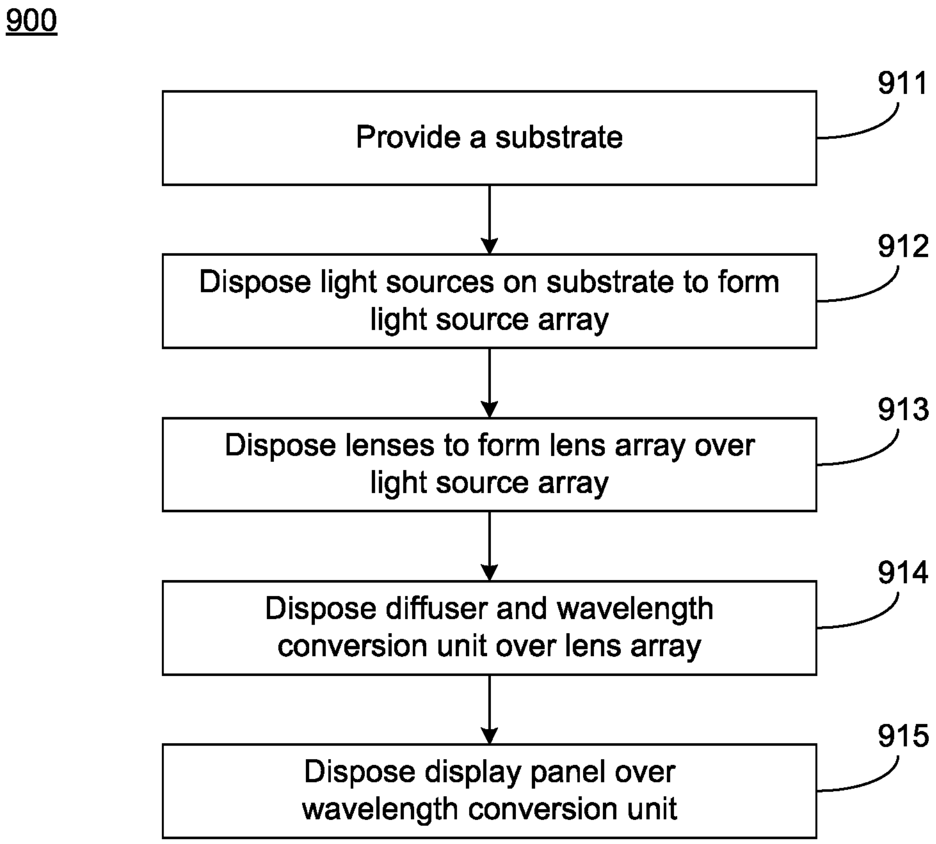
900
Provide a substrate
911
Dispose light sources on substrate to form light source array
912
Dispose lenses to form lens array over light source array
913
Dispose diffuser and wavelength conversion unit over lens array
914
Dispose display panel over wavelength conversion unit
915

FIG. 9

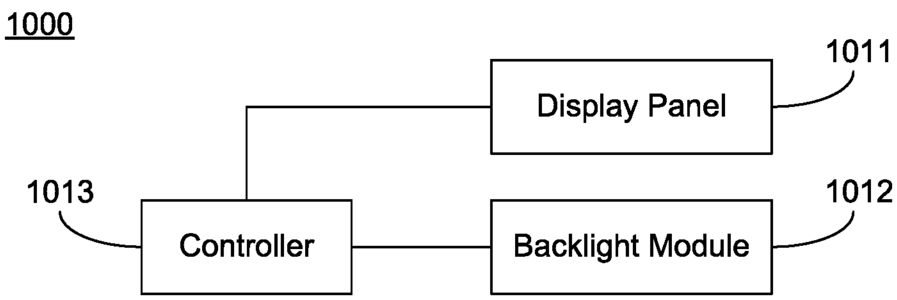
1000
Display Panel
1011
1013
Controller
Backlight Module
1012

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2022/071368

A. CLASSIFICATION OF SUBJECT MATTER

G02F 1/13357(2006.01)i； F21V 5/00(2018.01)i； G02B 5/02(2006.01)i

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)

G02F, F21V, G02B

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

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

CNPAT;CNKI;WPI;EPODOC: display, backlight, light source, LED, grid, matrix, array, rectangle, four, lens, X, Y, direction, axis, luminance, value, function

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CN 211627972 U (GUANGZHOU SHIYUAN ELECTRONICS TECHNOLOGY et al.) 02 October 2020 (2020-10-02) claims 1-10, description paragraphs [0040]-[0052] and figures 4-6	1-10
Y	JP 2018073668 A (KURARAY CO.) 10 May 2018 (2018-05-10) claims 1-5, description paragraphs [0010]-[0083] and figures 1-10	1-10
X	TW 201207292 A (SUMITOMO CHEMICAL CO.) 16 February 2012 (2012-02-16) claims 1-4, description pages 4-19 and figures 1-11	11-20
A	TW 200834003 A (KURARAY CO.) 16 August 2008 (2008-08-16) the whole document	1-20
A	CN 1912716 A (SAMSUNG ELECTRONICS CO., LTD.) 14 February 2007 (2007-02-14) the whole document	1-20
A	WO 2021166431 A1 (FUJIFILM CORP.) 26 August 2021 (2021-08-26) the whole document	1-20
A	WO 2021166433 A1 (FUJIFILM CORP.) 26 August 2021 (2021-08-26) the whole document	1-20

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

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

Date of the actual completion of the international search	Date of mailing of the international search report
15 September 2022	**28 September 2022**

Name and mailing address of the ISA/CN	Authorized officer
National Intellectual Property Administration, PRC **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088, China**	**ZHONG,Jie**
Facsimile No. **(86-10)62019451**	Telephone No. **86-(10)-53962618**

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WANG, Wei et al. "Design of Freeform Lens for Optimization of Luminous Intensity Distribution Based on Luminance Coefficient" *ZHAOMING GONGCHENG XUEBAO,* 15 April 2013 (2013-04-15),	1-20

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2022/071368

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
CN	211627972	U	02 October 2020	None			
JP	2018073668	A	10 May 2018	JP	6679465	B2	15 April 2020
TW	201207292	A	16 February 2012	JP	2011129371	A	30 June 2011
				WO	2011074644	A1	23 June 2011
				JP	5075190	B2	14 November 2012
TW	200834003	A	16 August 2008	WO	2008029911	A1	13 March 2008
				JP	WO2008029911	A1	21 January 2010
CN	1912716	A	14 February 2007	TW	200707027	A	16 February 2007
				US	2007035679	A1	15 February 2007
				KR	20070019816	A	15 February 2007
				KR	695016	B1	16 March 2007
WO	2021166431	A1	26 August 2021	TW	202132720	A	01 September 2021
WO	2021166433	A1	26 August 2021	TW	202202918	A	16 January 2022