



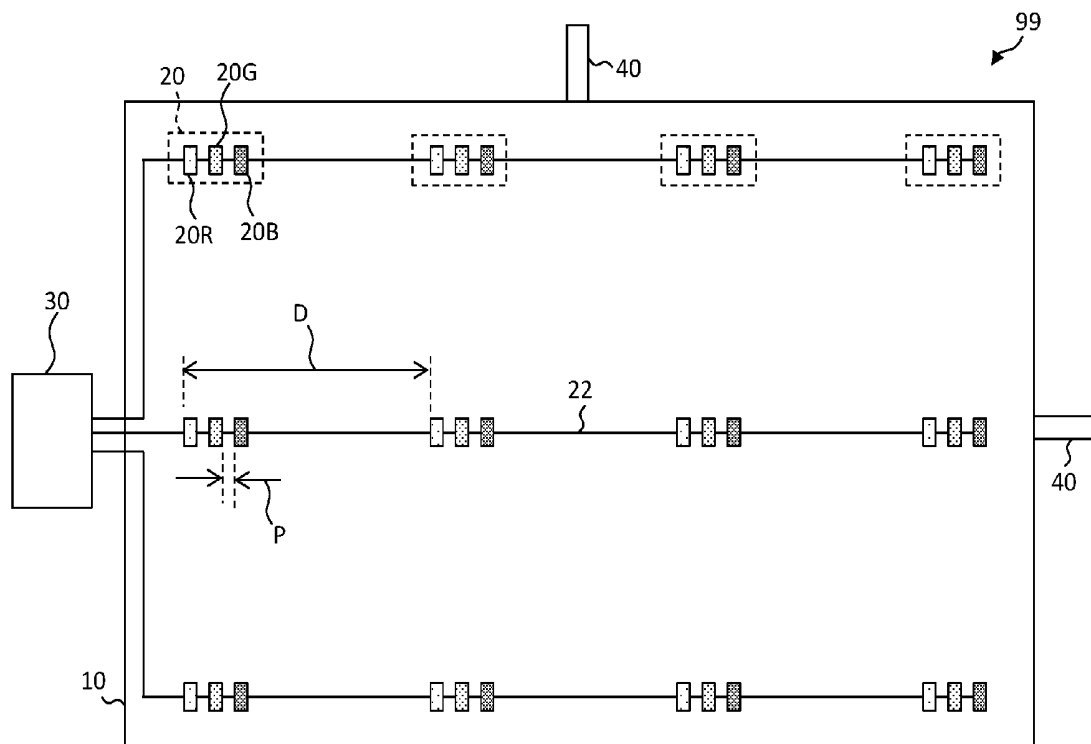
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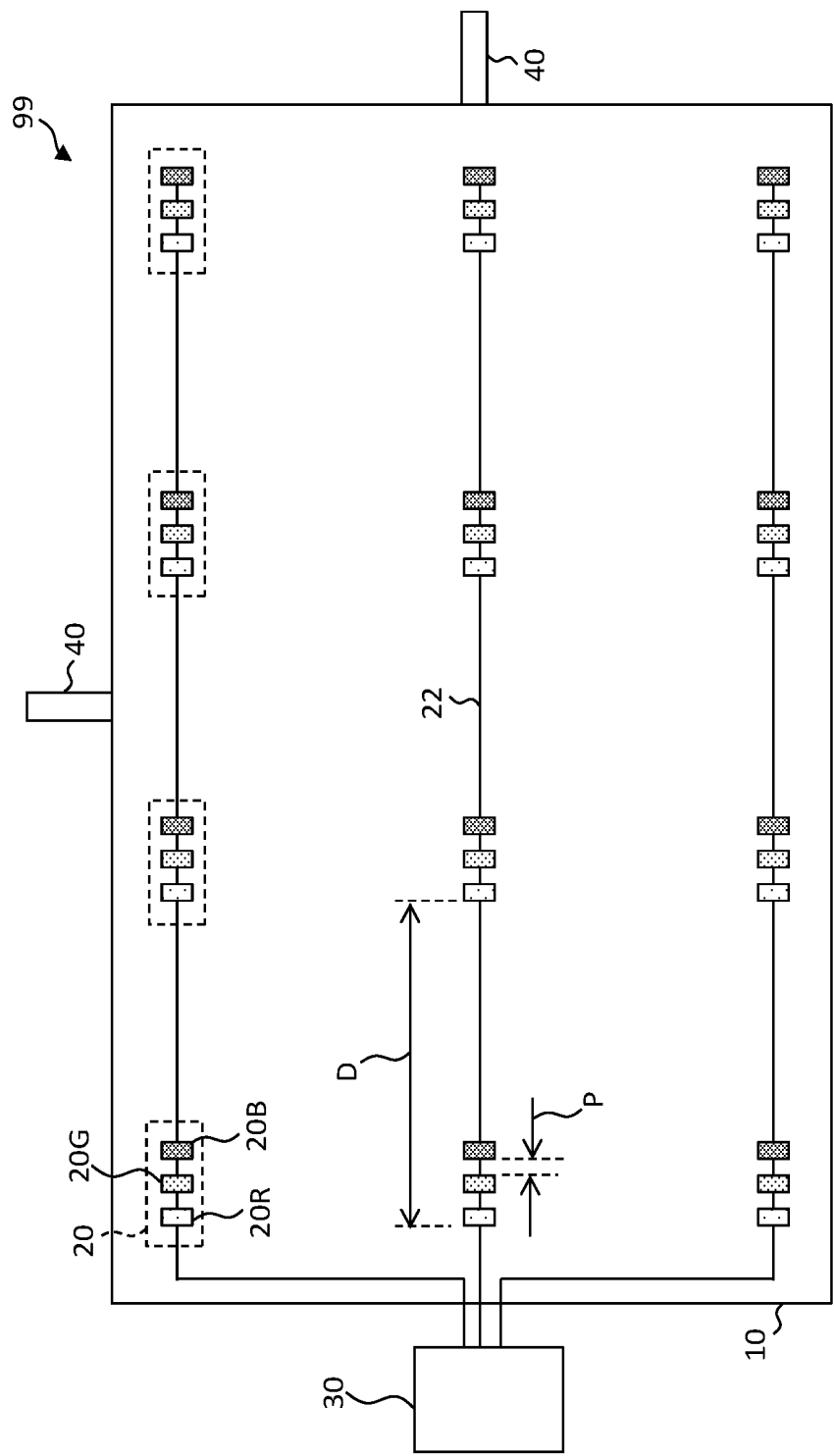
(19) **United States**(12) **Patent Application Publication** (10) **Pub. No.: US 2018/0130400 A1**  
(43) **Pub. Date: May 10, 2018**(54) **SPATIALLY DITHERED HIGH-RESOLUTION DISPLAYS**(71) Applicant: **X-Celeprint Limited**, Cork (IE)(72) Inventors: **Matthew Meitl**, Durham, NC (US);  
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**Christopher Bower**, Raleigh, NC (US)(21) Appl. No.: **15/808,126**(22) Filed: **Nov. 9, 2017****Related U.S. Application Data**

(60) Provisional application No. 62/420,529, filed on Nov. 10, 2016.

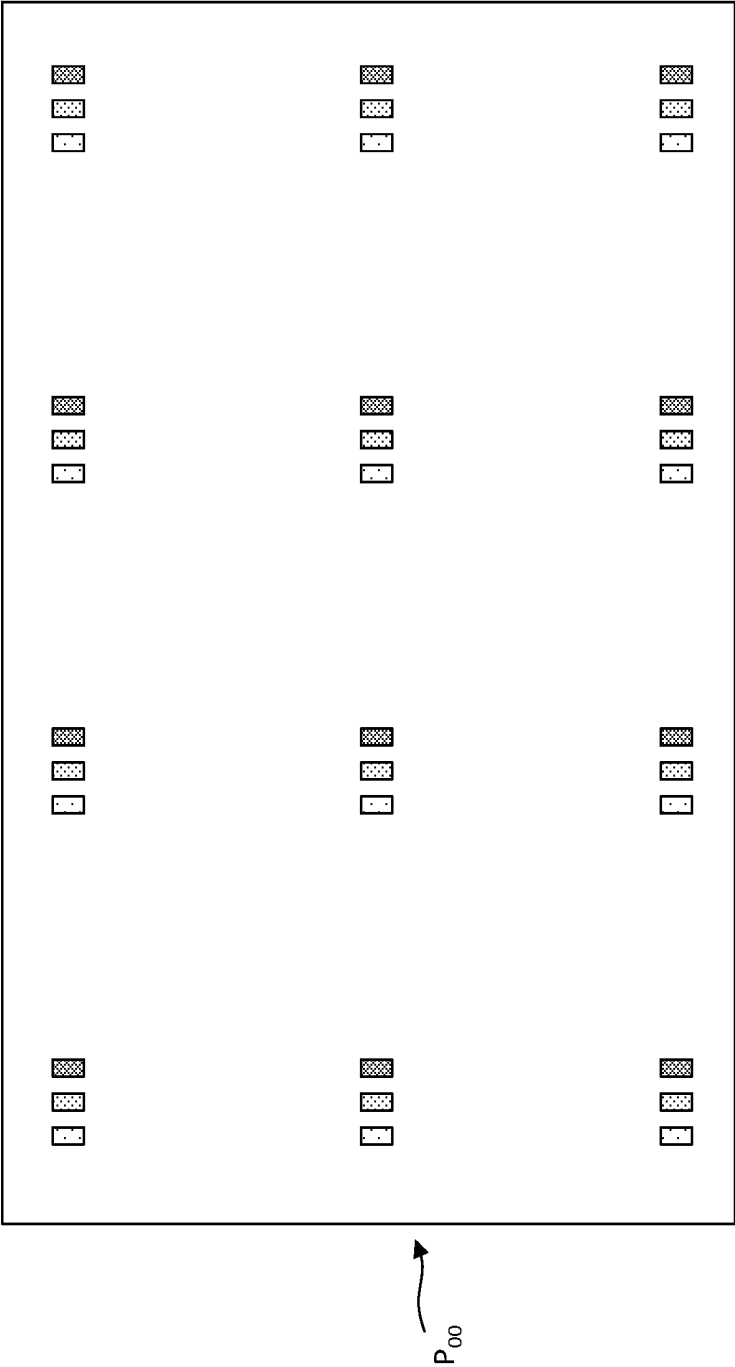
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**2320/0666** (2013.01); **G09G 2320/0247**  
(2013.01); **G09G 3/32** (2013.01)(57) **ABSTRACT**

A high-resolution display includes a display substrate having an array of light-emitting display pixels disposed thereon for displaying an image comprising an array of image pixels. The total number of display pixels in the array of light-emitting display pixels is less than and evenly divides the total number of image pixels in the image in at least one dimension. An actuator physically moves a display substrate and light-emitting display pixels in one or two dimensions in a direction parallel to a surface of the display substrate. A controller controls the light-emitting operation of display pixels and controls physical location of the display pixels. In some embodiments, a controller controls an actuator to spatially interpolate the spatial location of display pixels at successive times and controls the light-emitting operation of display pixels to display a different subset of the image pixels at each successive time.

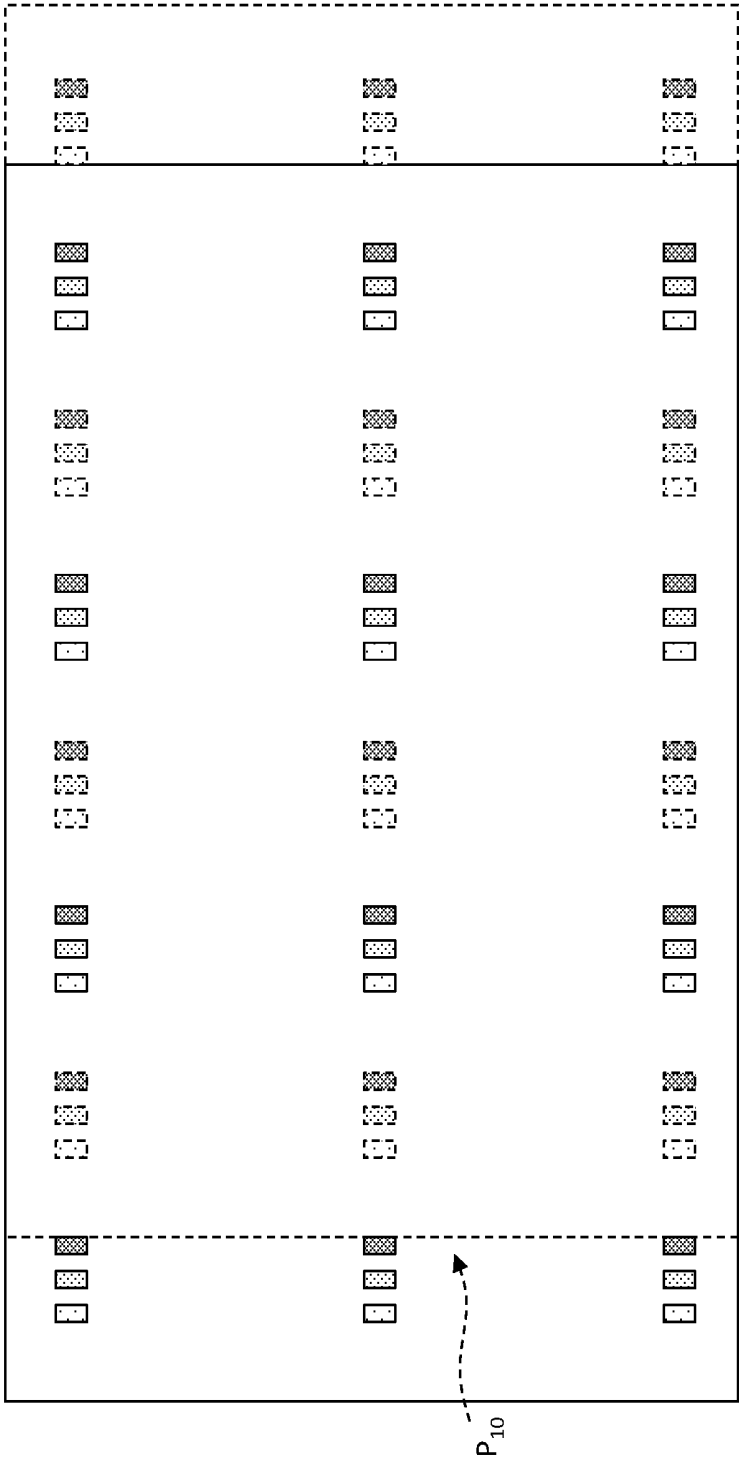




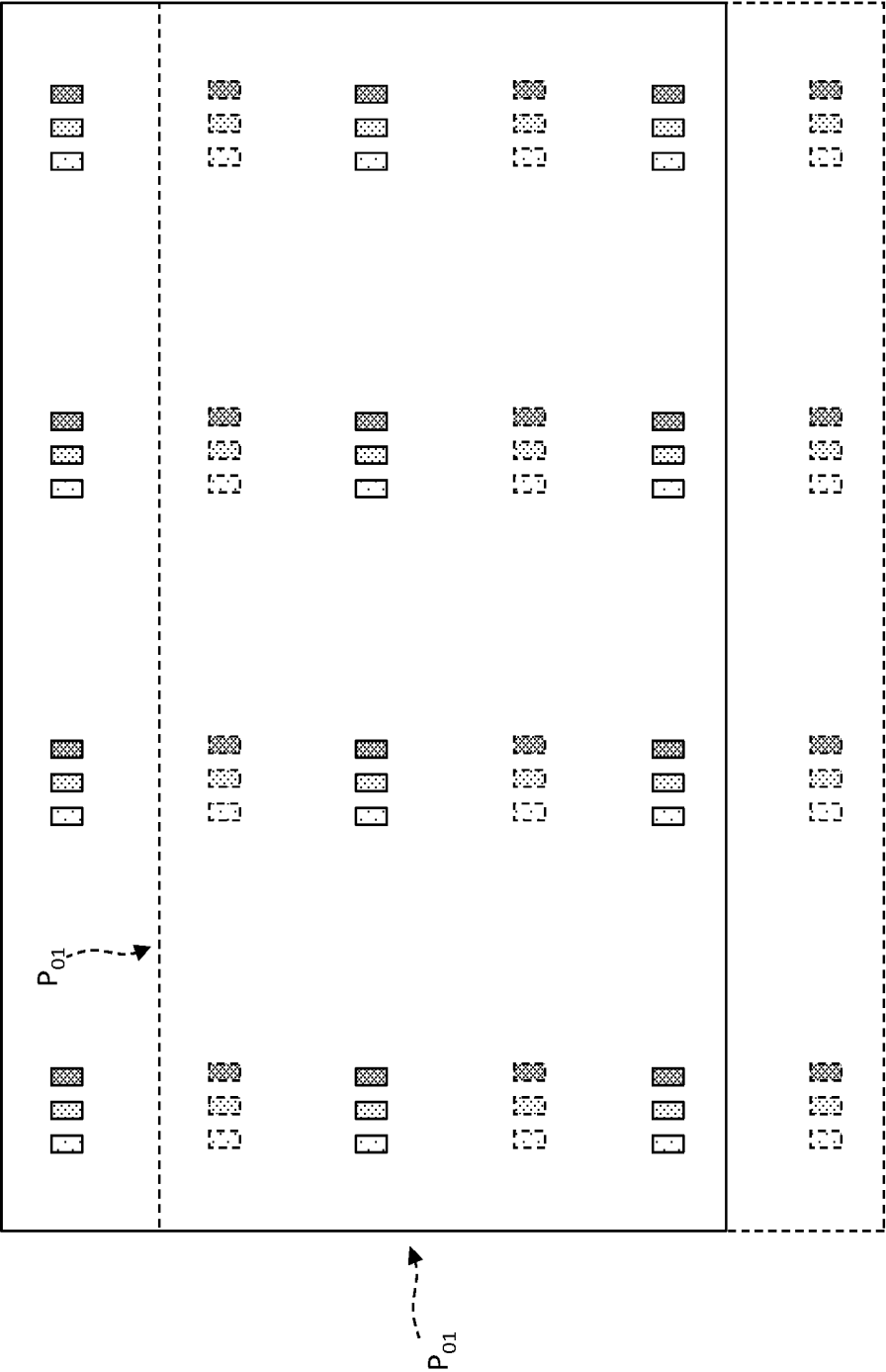
**FIG. 1**



**FIG. 2A**



**FIG. 2B**



**FIG. 2C**

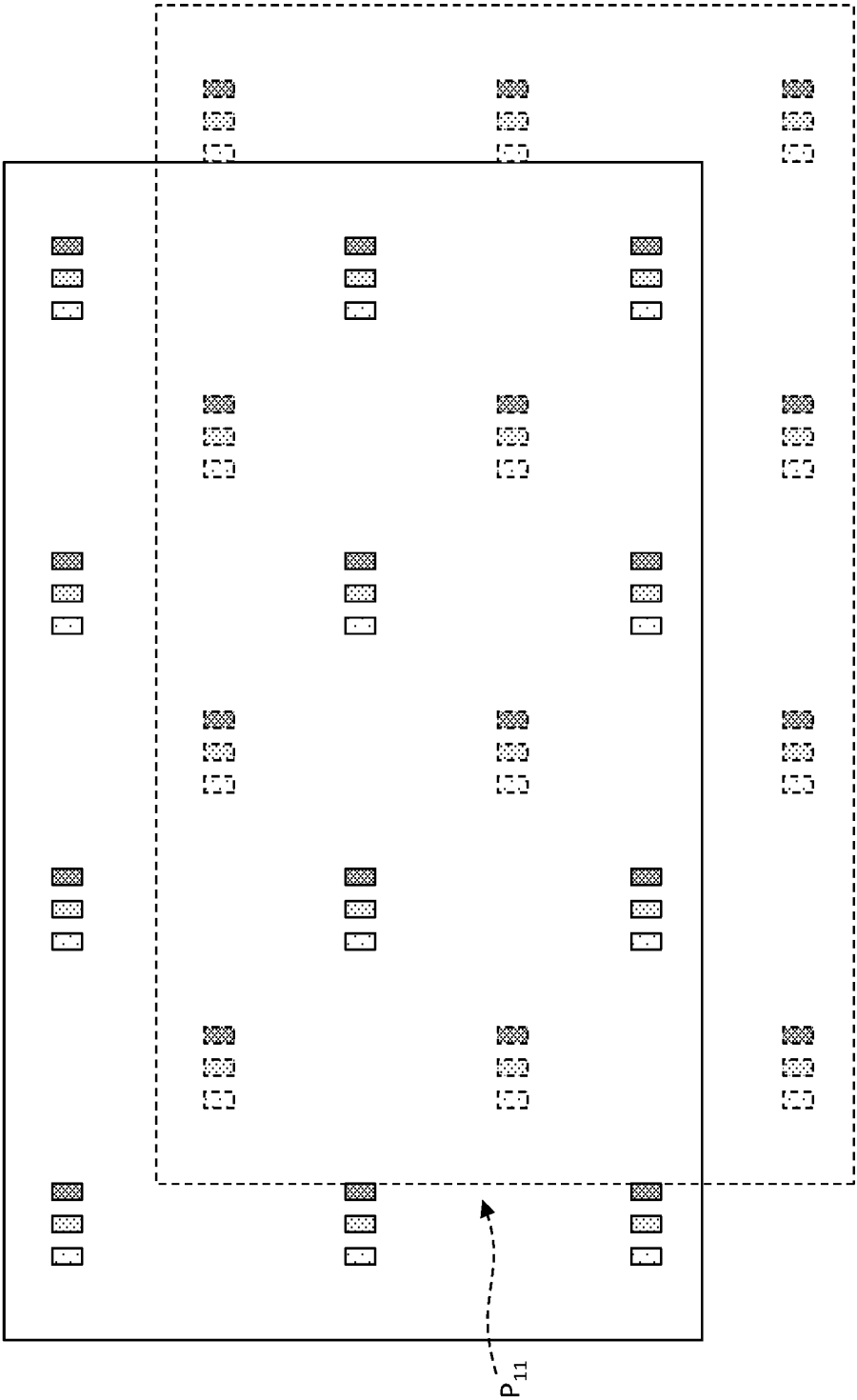


FIG. 2D

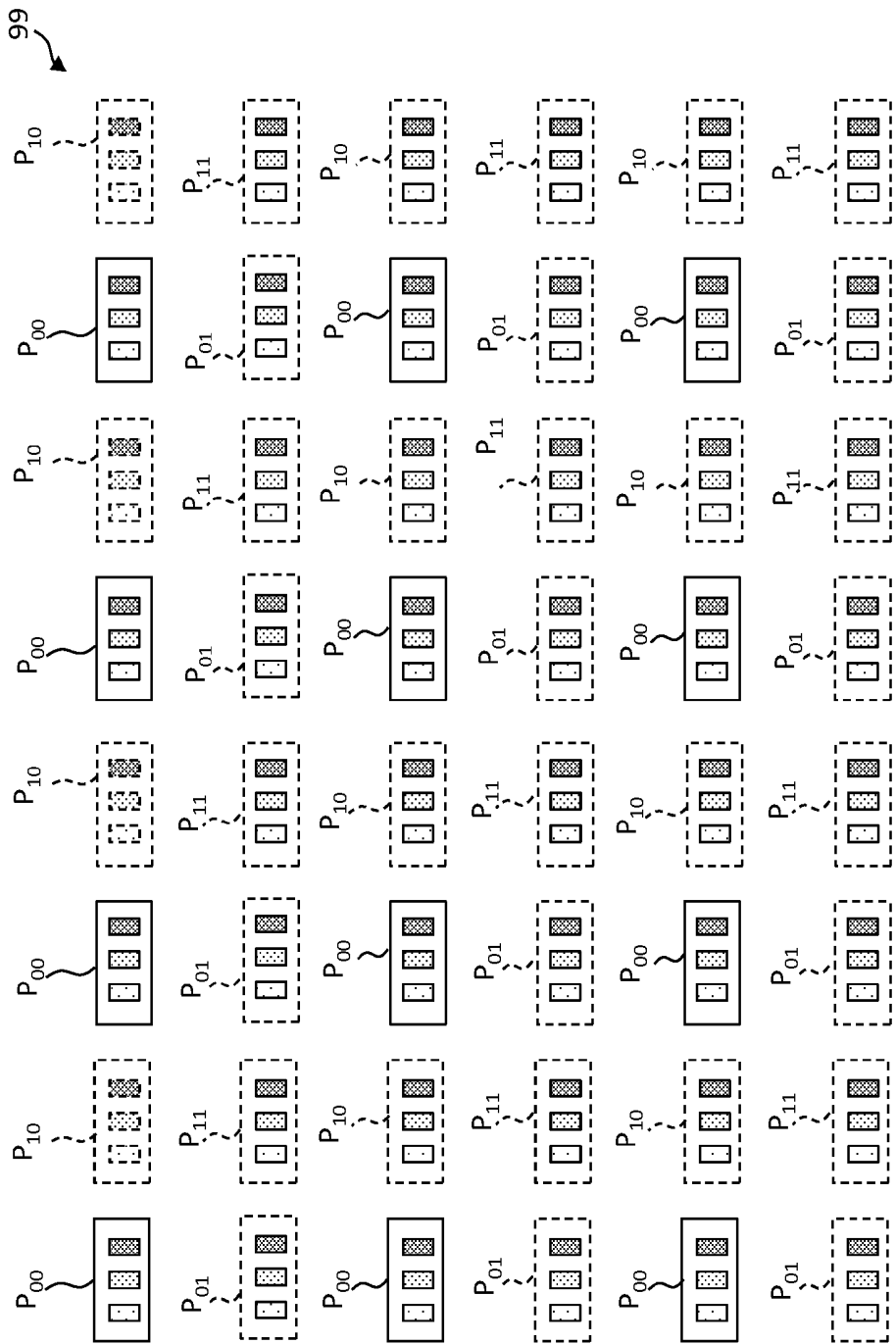
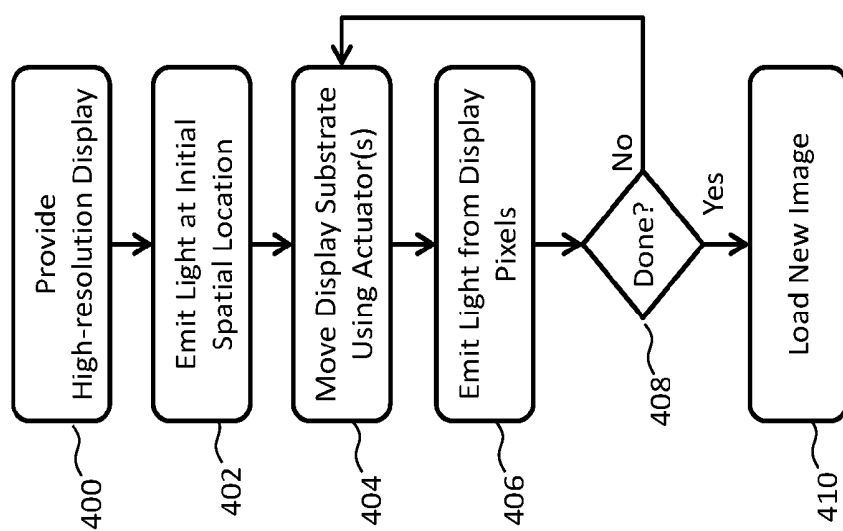
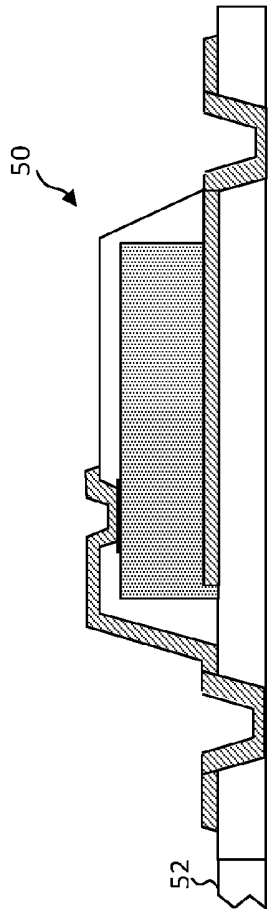


FIG. 3

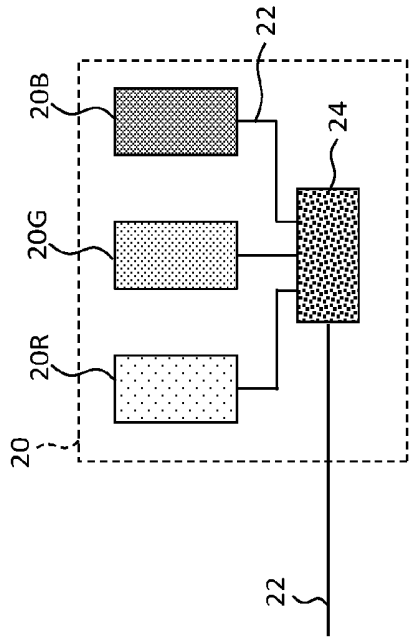


**FIG. 4**





**FIG. 5**



**FIG. 6**

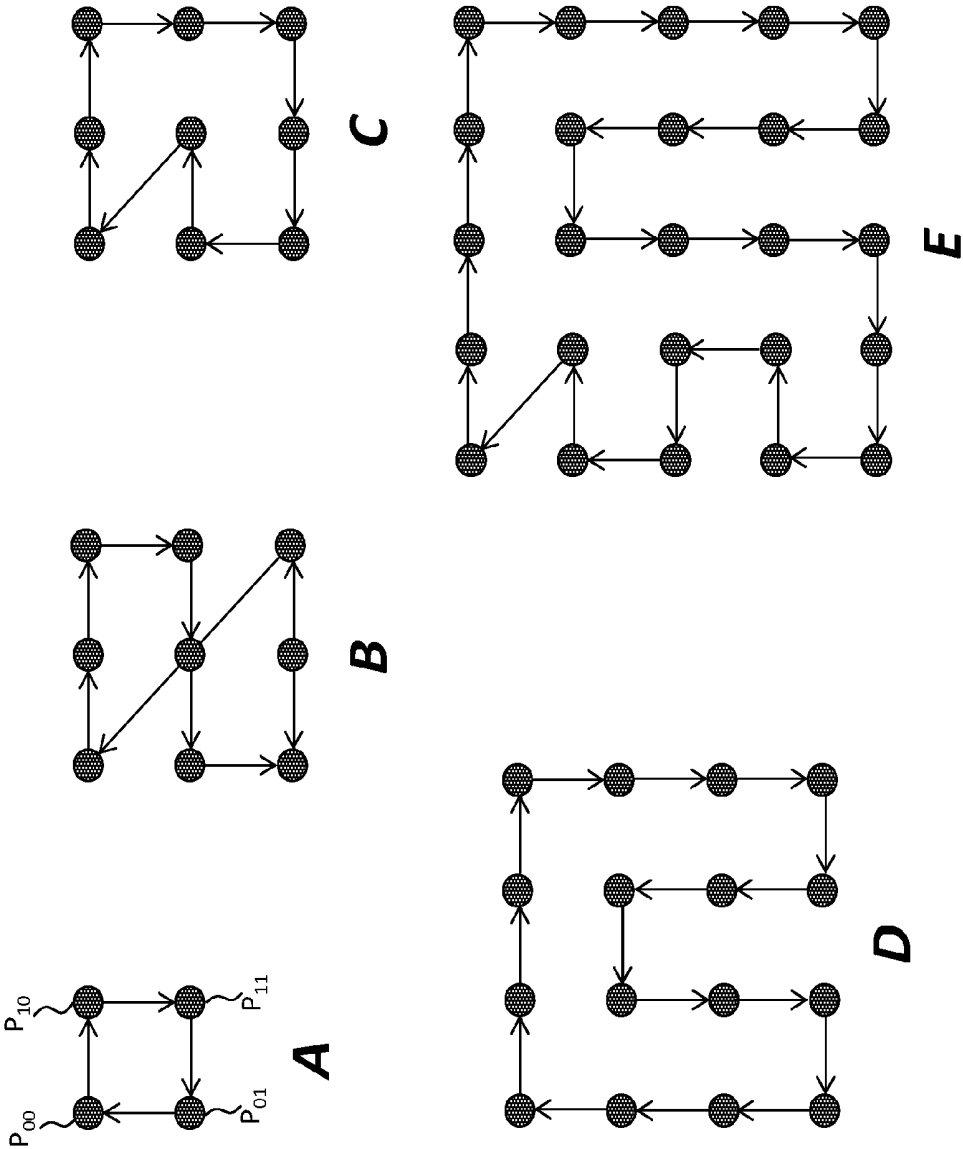
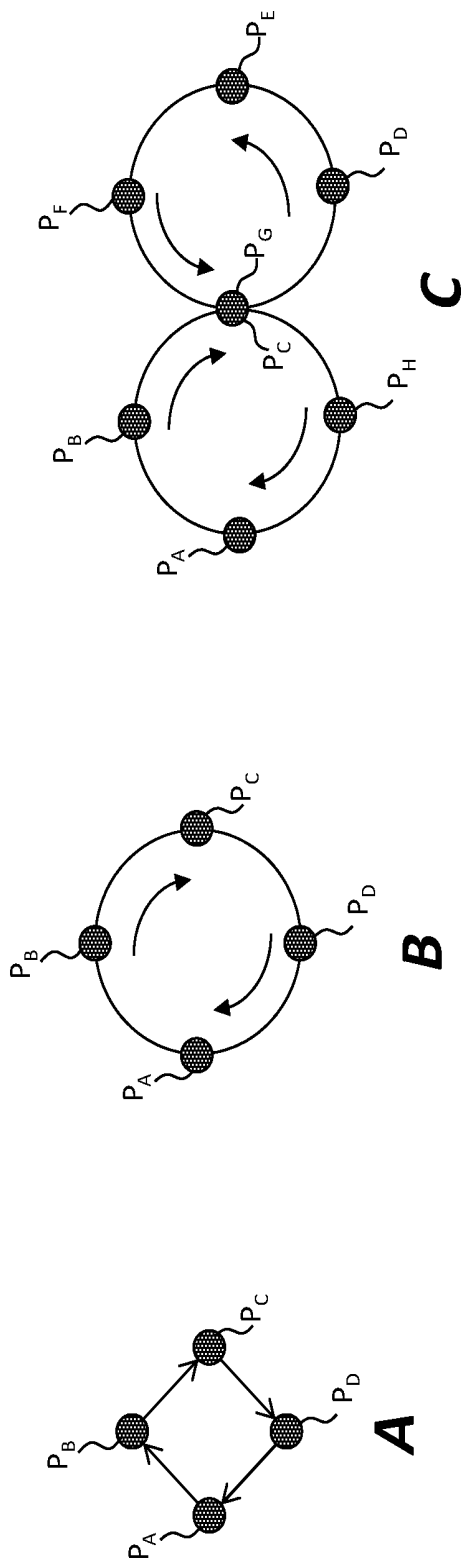
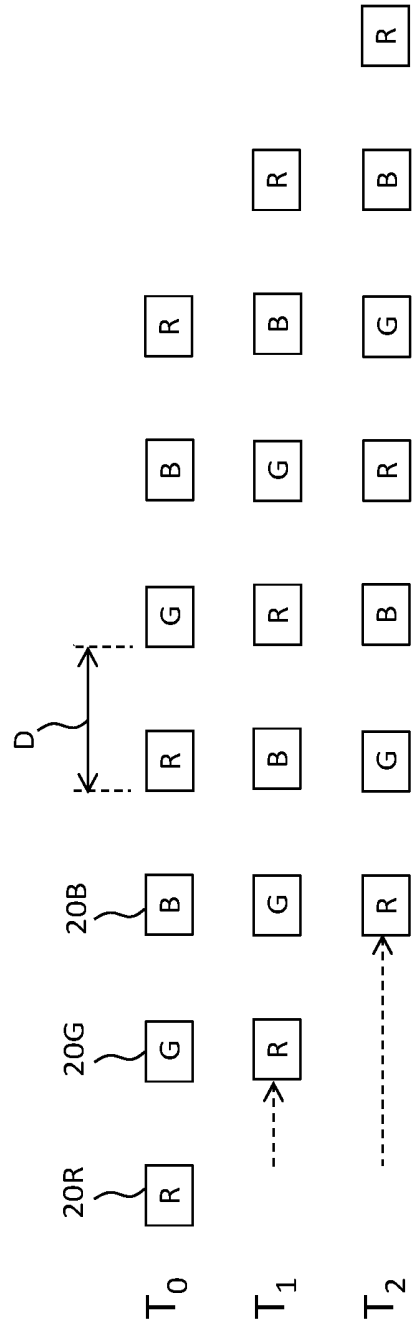


FIG. 7



**FIG. 8**



**FIG. 9**

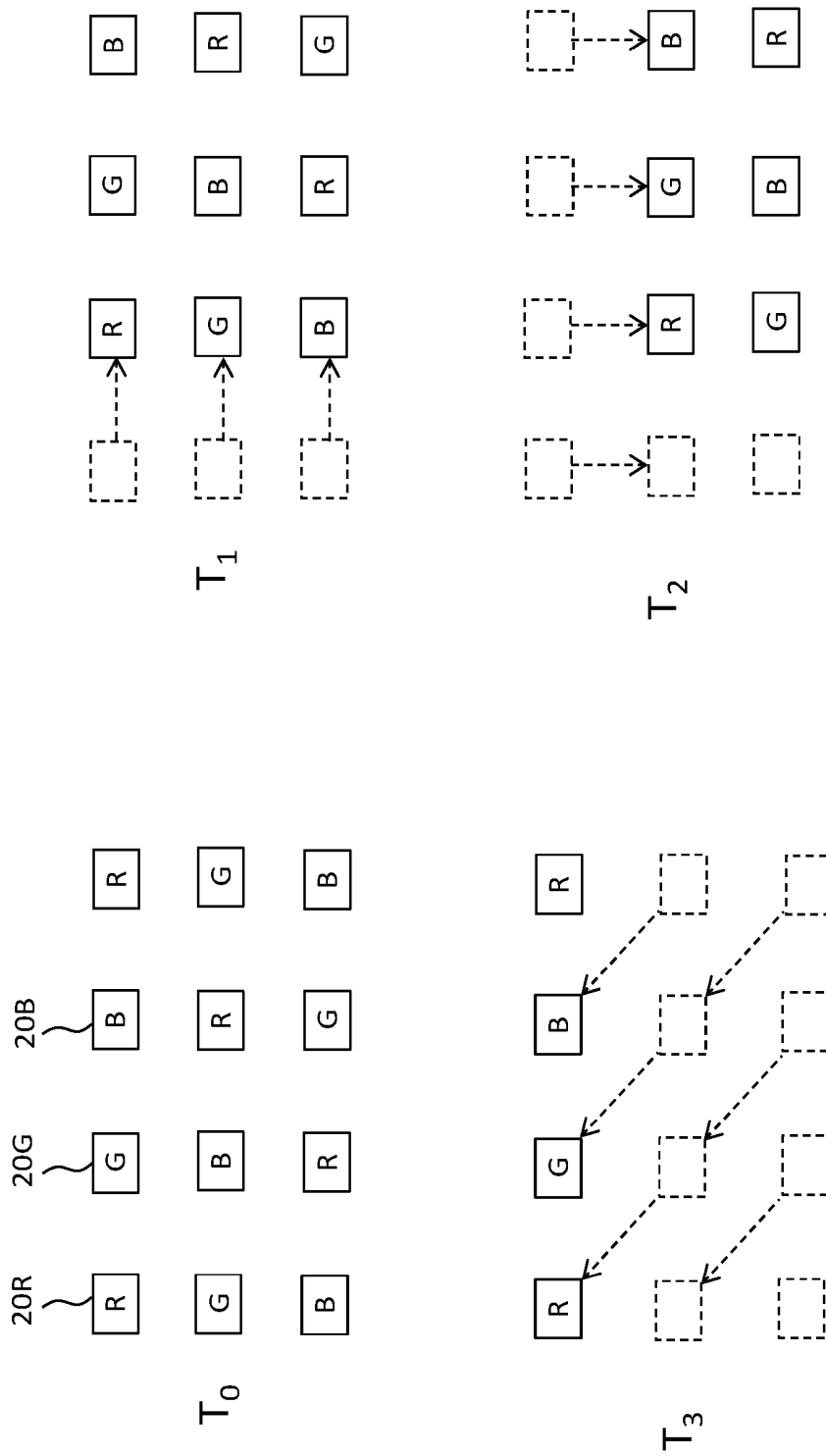
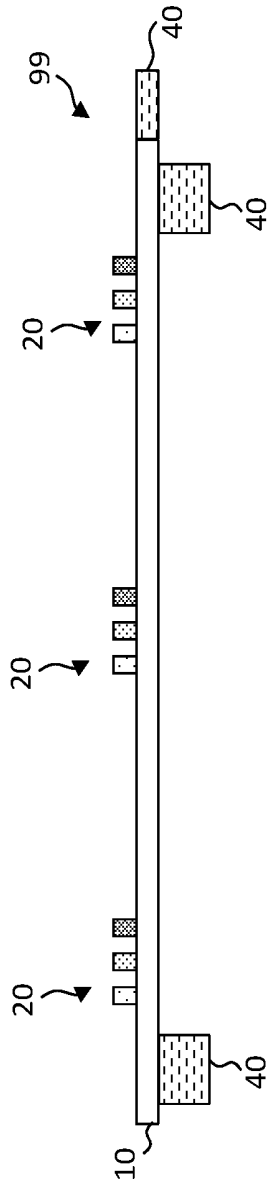
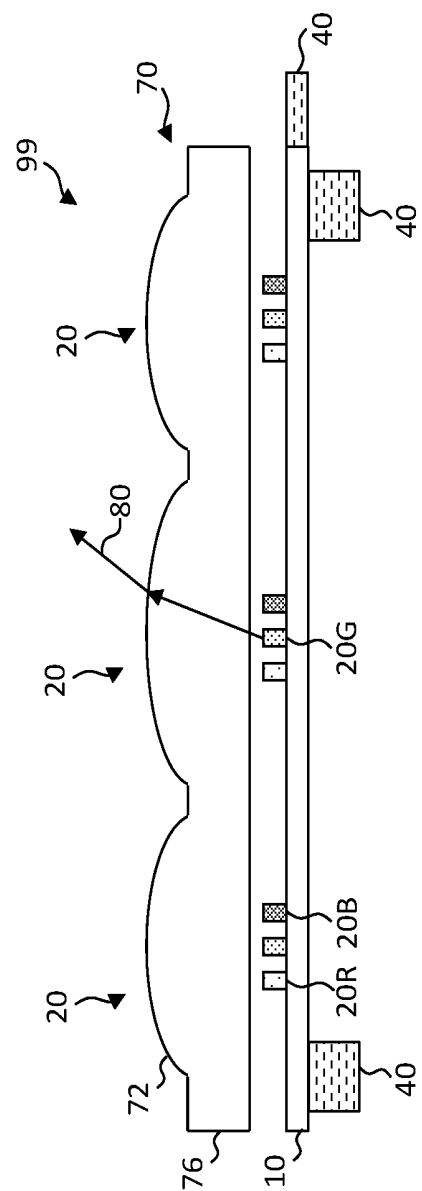


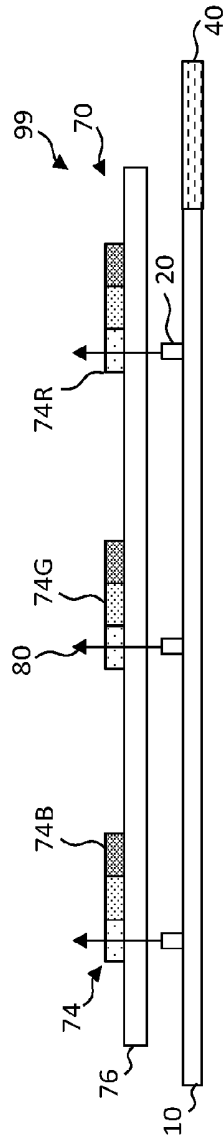
FIG. 10



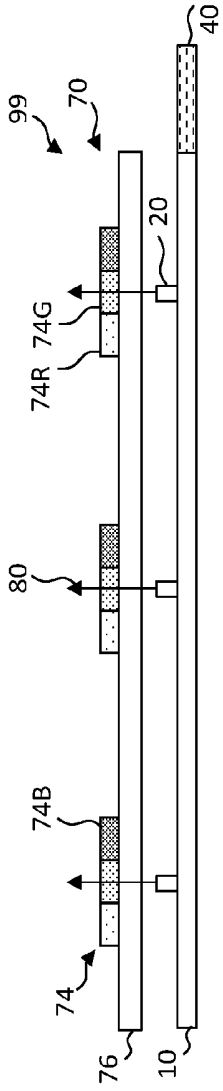
**FIG. 11**



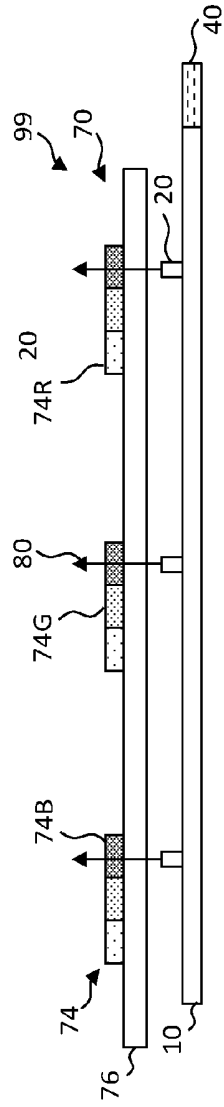
**FIG. 12**



**FIG. 13A**

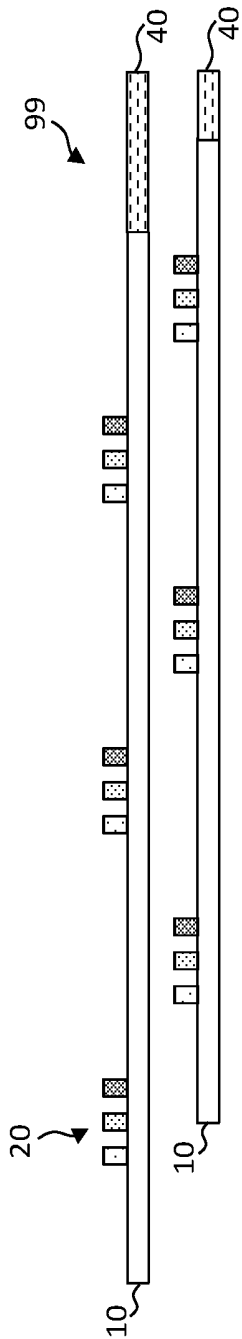


**FIG. 13B**

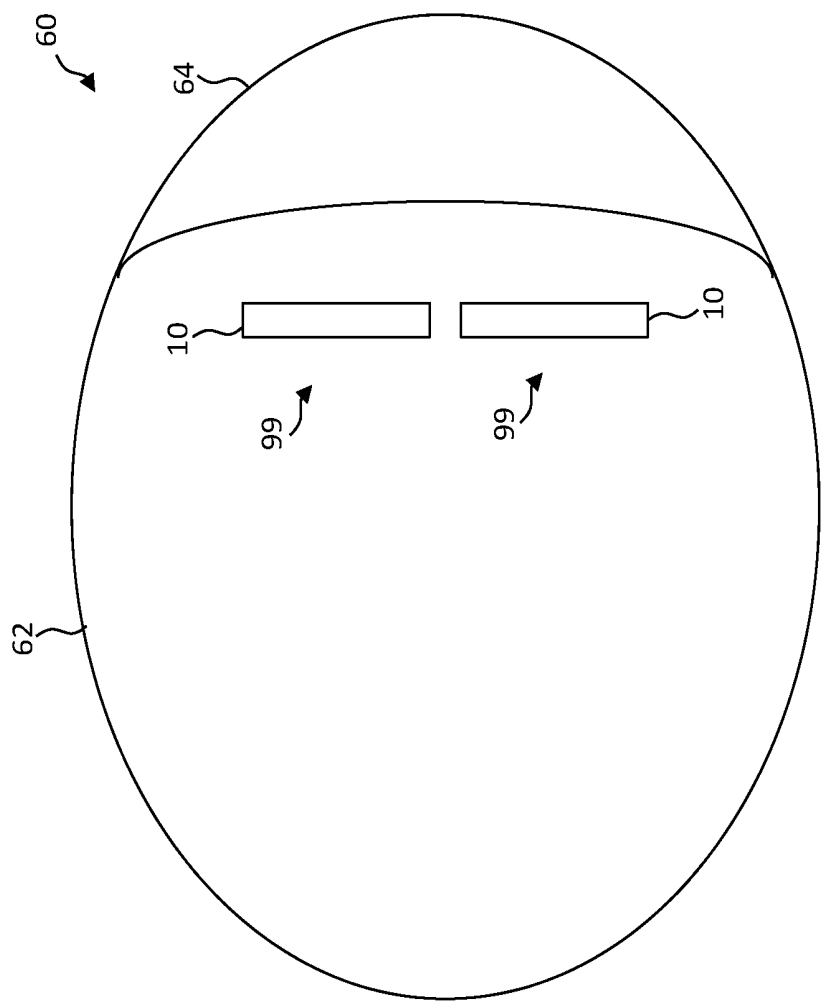


**FIG. 13C**





**FIG. 14**



**FIG. 15**

## SPATIALLY DITHERED HIGH-RESOLUTION DISPLAYS

### PRIORITY APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/420,529, filed Nov. 10, 2016, entitled “Spatially Dithered High-Resolution Display”, the disclosure of which is incorporated by reference herein in its entirety.

### FIELD OF THE INVENTION

[0002] The present invention relates generally to high-resolution displays.

### BACKGROUND OF THE INVENTION

[0003] Displays are widely used to present information to viewers. In general, more information can be presented more clearly with displays having greater resolution. Moreover, displays with greater resolution are often more pleasing to viewers.

[0004] A variety of techniques have been proposed for presenting lower-resolution imagery on a higher-resolution display, for example using inter-pixel interpolation to increase the number of pixels in the image to match the number of pixels in the higher-resolution display. Other techniques, for example as taught in U.S. Pat. No. 8,179,401 use dither patterns for sequentially displaying groups of pixels, particularly for addressing motion artifacts in color sequential displays, but does not actually improve the apparent resolution of the display.

[0005] U.S. Pat. No. 6,574,032 discusses the use of a spatial light modulator to move the apparent location of light emitted by pixels. The spatial light modulator effectively enlarges the apparent pixel size to improve the fill factor. However, this approach does not actually improve the apparent resolution of the display.

[0006] U.S. Pat. No. 6,552,740 describes a printer using a spatial light modulator and proposes to duplicate pixel data by imaging the same data at multiple sites. This method can be used to create multiple overlapped images for the purpose of minimizing effects of pixel site defects in the spatial light modulator. Dithering is also proposed as a method for increasing the effective image resolution by printing a first image with the spatial light modulator in a first position, printing a second image with the spatial light modulator in a second position, and so on. This method can be used to increase image resolution by a multiple of two or four, depending on the dither pattern. However, this approach requires moving a relatively large spatial light modulator and requires a backlight.

[0007] There is a need, therefore, for devices, systems and methods for improving the apparent resolution of displays.

### SUMMARY OF THE INVENTION

[0008] In one aspect, the present invention is directed to a high-resolution display, comprising: a display substrate; an array of light-emitting display pixels disposed on the display substrate; at least one actuator for physically moving the display substrate and the array of light-emitting display pixels to different physical locations in at least one dimension in a direction parallel to a surface of the display substrate; a controller for controlling the light-emitting operation of the display pixels and for controlling a spatial

location of the display pixels; and wherein the controller controls the at least one actuator to interpolate the spatial location of the display pixels at successive times and controls the light-emitting operation of the display pixels to display a different subset of image pixels in an image at each successive time, wherein a total number of display pixels in the array of light-emitting display pixels is less than and evenly divides a total number of image pixels in the image in at least one dimension (e.g., wherein the number of image pixels is an integral multiple greater than one of the number of display pixels in at least one dimension).

[0009] In certain embodiments, the display pixels are color pixels comprising two or more light-emitting sub-pixels and the controller controls the sub-pixels to emit light of different colors. In certain embodiments, each display pixel is a single-color display pixel and adjacent display pixels emit different single-colors of light.

[0010] In certain embodiments, each spatial location of the display pixels that the controller controls the at least one actuator to move the display substrate to at a successive time of the successive times corresponds to a relative location of image pixels in the image displayed by the display pixels at the successive time.

[0011] In certain embodiments, a total number of spatial locations the controller controls the at least one actuator to move to is the same as the total number of image pixels in the image.

[0012] In certain embodiments, the spatial locations are interpolated in one dimension. In certain embodiments, the spatial locations are interpolated in two directions. In certain embodiments, the two directions are two orthogonal directions.

[0013] In certain embodiments, the spatial locations at successive times correspond to adjacent image pixels in the image.

[0014] In certain embodiments, the controller controls the at least one actuator to move continuously along a dither pattern.

[0015] In certain embodiments, each display pixel is separated from a neighboring pixel by a pixel separation distance and each of the at least one actuator has a range of motion for moving the display substrate that is at least equal to the pixel separation distance (e.g., at least equal to twice the pixel separation distance).

[0016] In certain embodiments, the display comprises an actuator for physically moving the display substrate and the array of light-emitting display pixels in a direction orthogonal to a surface of the display substrate on which the array of light-emitting display pixels are disposed.

[0017] In certain embodiments, the display substrate is substantially transparent and the high-resolution display comprises at least one additional display substrate each comprising an array of light-emitting display pixels disposed thereon and at least one actuator for physically moving the additional display substrate and the array of light-emitting display pixels disposed thereon to different spatial locations at least one dimension parallel to a surface of the display substrate, wherein the display substrate and the at least one additional display substrate form a stack of display substrates.

[0018] In certain embodiments, each display pixel is separated from a neighboring display pixel by a pixel separation distance and each of the at least one actuator has a range of

motion for moving the display substrate of at least one half (e.g., at least two thirds or at least three quarters) of the pixel separation distance.

**[0019]** In certain embodiments, each display pixel is separated from a neighboring pixel by a pixel separation distance, wherein the display pixels are color pixels comprising two or more light-emitting sub-pixels, and the two or more light-emitting sub-pixels in a color pixel are separated by a distance that is less than or equal to one quarter of the pixel separation distance.

**[0020]** In certain embodiments, the light-emitting pixels comprise inorganic micro-light-emitting diodes comprising at least one of a length, a width, and a thickness that is less than or equal to twenty microns (e.g., less than or equal to ten microns, five microns, two microns, or one micron).

**[0021]** In certain embodiments, each sub-pixel comprises at least one micro-transfer printed micro-light-emitting diode comprising a fractured or separated tether.

**[0022]** In certain embodiments, each light-emitting display pixel in the array of light-emitting display pixels comprises an active-matrix pixel controller.

**[0023]** In certain embodiments, the at least one actuator is (i) one or more piezo actuators disposed to move the display substrate in one dimension; (ii) two or more piezo actuators disposed to move the display substrate in two dimensions (e.g., two orthogonal dimensions); or (iii) three or more piezo actuators disposed to move the display substrate in three dimensions (e.g., three orthogonal dimensions).

**[0024]** In certain embodiments, the display comprises an optical structure disposed over the array of display pixels such that light emitted by the display pixels is optically processed by the optical structure, wherein the at least one actuator is for moving the display substrate relative to the optical structure.

**[0025]** In certain embodiments, the at least one actuator moves the display substrate in at least one of (i) at least a portion of a straight line segment, a curved line segment, a circle, a circular line segment, a sinusoidal line segment, a sine wave, and (ii) a resonant mechanical mode in one or both of a horizontal plane parallel and a vertical plane orthogonal to a surface of the display substrate on which the array of light-emitting display pixels are disposed.

**[0026]** In certain embodiments, the display comprises a head set, wherein at least the display substrate, the array of light-emitting display pixels, and the at least one actuator are mounted to the head set.

**[0027]** In another aspect, the present invention is directed to a method of displaying images on a high-resolution display using spatial dithering, wherein the high-resolution display comprises a display substrate, an array of light-emitting display pixels disposed on the display substrate, at least one actuator for physically moving the display substrate and the array of light-emitting display pixels to different physical locations in at least one dimension in a direction parallel to a surface of the display substrate, and a controller for controlling the light-emitting operation of the display pixels and for controlling a spatial location of the display pixels and the method comprises the steps of: (a) emitting light from the array of display pixels while the display pixels are in an initial spatial location, wherein the emitted light corresponds to a subset of image pixels of an image and a total number of display pixels in the array of light-emitting display pixels is less than and evenly divides a total number of image pixels in the image in at least one

dimension (e.g., wherein the number of image pixels is an integral multiple greater than one of the number of display pixels in at least one dimension); (b) controlling, by the controller, movement of one or more of the at least one actuator to move the display substrate such that the array of display pixels are interpolated to a different spatial location along a dither pattern; (c) emitting light from the array of display pixels while the array is in the different spatial location along the dither pattern, wherein the light emitted from the array of display pixels while in the different spatial location corresponds to a different subset of image pixels in the image than the subset of image pixels in the; and (d) repeating step (b) and step (c) until light has been emitted from the array of display pixels in each spatial location, thereby displaying the image.

**[0028]** In certain embodiments, the dither pattern is a 2x2 pattern, a 3x3 pattern, a 4x4 pattern, or a 5x5 pattern. In certain embodiments, spatial locations are interpolated along the dither pattern in one dimension. In certain embodiments, spatial locations are interpolated along the dither pattern in two directions. In certain embodiments, the two directions are two orthogonal directions.

**[0029]** In certain embodiments, each pair of successive spatial locations interpolated along the dither pattern corresponds to adjacent subsets of image pixels in the image.

**[0030]** In certain embodiments, at least one pair of successive spatial locations interpolated along the dither pattern corresponds to non-adjacent subsets of image pixels in the image (e.g., wherein one of the pair of successive spatial locations is the initial spatial location).

**[0031]** In certain embodiments, the array of display pixels are interpolated to successive spatial locations along the dither pattern by interpolating along at least a portion of a straight line segment, a curved line segment, a circle, a circular line segment, a sinusoidal line segment, or a sine wave.

**[0032]** In certain embodiments, the method comprises loading a second image to be displayed while moving, in response to the controller actuating the at least one actuator, the array of display pixels to the initial spatial position from a non-adjacent spatial location.

**[0033]** In certain embodiments, the high-resolution display comprises an orthogonal actuator for physically moving the display substrate and the array of light-emitting display pixels in a direction orthogonal to a surface of the display substrate on which the array of light-emitting display pixels are disposed, and the method comprises: controlling, by the controller, movement of the orthogonal actuator to move the display substrate such that the array of display pixels are interpolated to an orthogonal spatial location along the dither pattern, wherein the orthogonal spatial location is a spatial location that lies above or below a plane of the initial spatial location.

**[0034]** Some embodiments of the present invention provide a high-resolution display suitable for small, light-weight display systems at a relatively low cost and in a robust structure.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0035]** The foregoing and other objects, aspects, features, and advantages of the present disclosure will become more apparent and better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

[0036] FIG. 1 is a plan view schematic illustration of a display, according to illustrative embodiments of the present invention;

[0037] FIGS. 2A-2D illustrate display pixel locations for a 2×2 spatial dither, according to illustrative embodiments of the present invention;

[0038] FIG. 3 is a plan view schematic illustration of the interpolated display pixel locations for the 2×2 dither pattern of FIGS. 2A-2D, according to illustrative embodiments of the present invention;

[0039] FIG. 7 illustrates a flow chart of an exemplary method of displaying images on a high-resolution display, according to illustrative embodiments of the present invention;

[0040] FIG. 5 is a cross section of a micro-LED, according to illustrative embodiments of the present invention;

[0041] FIG. 6 is a plan view schematic illustration of color display pixel comprising a pixel controller (e.g., an active-matrix pixel controller), according to illustrative embodiments of the present invention;

[0042] FIG. 10 illustrates dither patterns, according to illustrative embodiments of the present invention;

[0043] FIG. 8 illustrates non-rectilinear dither patterns, according to illustrative embodiments of the present invention;

[0044] FIG. 9 illustrates one-dimensional dither patterns for single-color pixels, according to illustrative embodiments of the present invention;

[0045] FIG. 10 illustrates two-dimensional dither patterns for single-color pixels, according to illustrative embodiments of the present invention;

[0046] FIG. 11 is a cross section of a high-resolution display comprising z-direction actuators, according to illustrative embodiments of the present invention;

[0047] FIG. 12 is a cross section of a high-resolution display comprising an optical structure incorporating lenslets, according to illustrative embodiments of the present invention;

[0048] FIGS. 13A-13C are cross sections of a high-resolution display comprising an optical structure incorporating color filters at different times, according to illustrative embodiments of the present invention;

[0049] FIG. 14 is a cross section of a high-resolution display comprising a stack of display substrates, according to illustrative embodiments of the present invention; and

[0050] FIG. 15 is a schematic illustration of a head-mounted display, according to illustrative embodiments of the present invention.

[0051] The features and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. The figures are not drawn to scale since the variation in size of various elements in the Figures is too great to permit depiction to scale.

#### DETAILED DESCRIPTION OF THE INVENTION

[0052] Referring to FIG. 1, a high-resolution display 99 in accordance with some embodiments of the present invention includes a display substrate 10 having an array of light-emitting display pixels 20 disposed thereon. The high-resolution display can be used to display an image compris-

ing an array of image pixels. The display substrate 10 can be, for example, a glass substrate or a thin glass substrate having a thickness less than one mm, less than 0.5 mm, or less than 0.25 mm. The display substrate 10 can be rigid or flexible. The light-emitting display pixels 20 can be inorganic micro light-emitting-diodes 50 (as shown in FIG. 5) for example having at least one of a length, a width, and thickness that is less than or equal to twenty microns, ten microns, five microns, two microns, or one micron. The display pixels 20 can have a pixel separation distance of D and a sub-pixel separation distance of P. The micro light-emitting-diodes 50 can be micro-transfer printed LEDs having a fractured or separated tether 52.

[0053] The total number of display pixels 20 in the array of light-emitting display pixels is less than and evenly divides the total number of image pixels in the image in at least one dimension. That is, the total number of image pixels in images displayed on the display is an integral multiple of the total number of display pixels 20 in at least one dimension and, in some embodiments, in two orthogonal directions. For example, a display substrate 10 can include a 640×480 array of display pixels 20 and an image can include a 1280×960 array of image pixels so that the image has twice as many image pixels as the display substrate 10 has display pixels 20 in each of two dimensions and the image has four times as many image pixels as the display substrate 10 has display pixels 20.

[0054] One or more actuators 40 are disposed to physically move the display substrate 10 and light-emitting display pixels 20 in one or two dimensions in a direction parallel to a surface of the display substrate 10. For example, as shown in FIG. 1, a single actuator 40 can be disposed to press against each of two orthogonal sides of a rectangular display substrate 10 in a direction orthogonal to the corresponding edge of the rectangular display substrate 10 against which the actuators 40 press. Thus, the two actuators 40 together can move the display substrate 10 in two orthogonal directions in a plane horizontal to the display substrate 10 surface. In some embodiments (not shown in FIG. 1), two or more actuators 40 are disposed to move the display substrate 10 in a common direction. Such a multi-actuator 40 arrangement can help to prevent the display substrate 10 from rotating. Useful actuators 40 include piezoelectric actuators.

[0055] A display controller 30 controls the light-emitting operation of the display pixels 20 and controls the physical location of the display pixels 20 in space by controlling the one or more actuators 40. A display controller 30 can be, for example, an integrated circuit that is electrically connected to the display pixels 20 with wires 22 and that electrically controls the display pixels 20 to emit light and electrically controls the actuator 40 to move the display substrate 10. In some embodiments, a display controller 30 comprises two or more sub-controllers, for example one sub-controller to control light emission and one sub-controller to control actuator motion (e.g., wherein each sub-controller is an integrated circuit). Sub-controllers of a display controller 30 can be spatially separate. A display controller 30 controls an actuator 40 to spatially interpolate the spatial location of display pixels 20 (e.g., along a dither pattern, as described subsequently) at successive times and controls light-emitting operation of the display pixels 20 to display a different subset of the image pixels at each successive time.

[0056] In a simple example, a display substrate 10 includes a 640×480 array of display pixels 20 and an image

includes a 1280×960 array of image pixels so that the image has twice as many image pixels as the display substrate 10 has display pixels 20 in each of two dimensions.

[0057] Referring to FIG. 2A, at a first time  $T_0$  the display pixels 20 and the display substrate 10 are at a first location  $P_{00}$ , for example at rest with the actuator 40 in a neutral position. While in this position, the display controller 30 controls the display pixels 20 to emit light corresponding to every other image pixel in each of two orthogonal directions with an offset of zero in both dimensions, for example emitting light corresponding to the first, third, fifth and so on image pixels in each row and column. Thus, the display pixels 20 display a first subset of the image.

[0058] Referring to FIG. 2B, at a second time  $T_1$  the display pixels 20 and the display substrate 10 are at a second location  $P_{10}$ , for example spatially offset in the x direction by a distance that is one half of the pixel separation distance D (i.e., that is midway in the x dimension between the pixels in the neutral position  $P_{00}$ ). While in this position, the display controller 30 controls the display pixels 20 to emit light corresponding to every other image pixel in each of two orthogonal directions with an offset of one pixel in the x dimension and no offset in the y dimension, for example emitting light corresponding to the second, fourth, sixth and so on image pixels in each row and the first, third, fifth and so on image pixels in each column. Thus, the display pixels 20 display a second subset of the image.

[0059] Referring to FIG. 2C, at a third time  $T_2$  the display pixels 20 and the display substrate 10 is at a third location  $P_{01}$ , for example spatially offset in the y direction by a distance that is one half of the pixel separation distance D, that is midway in the y dimension between the pixels in the neutral position  $P_{00}$ . While in this position, the display controller 30 controls the display pixels 20 to emit light corresponding to every other image pixel in each of two orthogonal directions with an offset of zero pixels in the x dimension and an offset of one pixel in the y dimension, for example emitting light corresponding to the first, third, fifth and so on image pixels in each row and the second, fourth, sixth and so on image pixels in each column. Thus, the display pixels 20 display a third subset of the image.

[0060] Referring to FIG. 2D, at a fourth time  $T_3$  the display pixels 20 and the display substrate 10 is at a fourth location  $P_{11}$ , for example spatially offset in the y direction and in the x direction by a distance that is one half of the pixel separation distance D, that is midway in the x and y dimensions between the pixels in the neutral position  $P_{00}$ . While in this position, the display controller 30 controls the display pixels 20 to emit light corresponding to every other image pixel in each of two orthogonal directions with an offset of one pixel in the x dimension and an offset of one pixel in the y dimension, for example emitting light corresponding to the second, fourth, sixth and so on image pixels in each row and the second, fourth, sixth and so on image pixels in each column. Thus, the display pixels 20 display a fourth subset of the image and the complete image is displayed at the image resolution in a 2×2 dither pattern over the time taken by times  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$ , as shown in FIG. 3.

[0061] FIG. 4 is a flow chart of an exemplary method to display one or more images using a high-resolution display in accordance with some embodiments of the present invention. In a providing step 400, a high-resolution display 99 is provided. For example, a high-resolution display 99 in

accordance with FIG. 1 can be provided. In an initial emitting step 402, an array of display pixels 20 emits light (e.g., corresponding to a first subset of image pixels of the image). In a moving step 404, one or more actuators 40 move a display substrate 10 on which the display pixels 20 are disposed. The display pixels 20 are interpolated along a dither pattern as a result of the one or more actuators 40 moving the display substrate 10 in correspondence with the dither pattern (e.g., in accordance with FIGS. 2A-2D and FIG. 3, as described above). In an emitting step 406, light is emitted from light-emitting display pixels 20 disposed on the display substrate 10. For example, light emitted from the display pixels 20 can correspond to image pixels in the image being displayed during the method. In some embodiments, light is continuously emitted from display pixels 20 as the one or more actuators 10 move the display substrate (e.g., step 404 and step 406 occur simultaneously).

[0062] In a determining step 408, a determination is made as to whether each spatial location in the dither pattern has been interpolated for the image. If not, then the method repeats the moving step 404 and the emitting step 406 (e.g., multiple times). For example, in some embodiments using a 2×2 dither pattern, a moving step 404 and emitting step 406 are performed three times for each image (e.g., frame of a video). If each spatial location has been interpolated, then a new image is loaded in a loading step 410. In some embodiments, a new image is loaded into the display 99 (e.g., into a controller 30 of the display 99) as the one or more actuators 40 move the array of display pixels 20 back to an initial spatial location. In some embodiments, a new image is loaded after display pixels 20 return to an initial spatial position.

[0063] In order to avoid perceptible flicker in a display, it is necessary to display the image pixel subsets at a rate greater than, for example 30 frames per second, the frame rate of the commercial analog NTSC television standard. In some embodiments of the present invention, a high-resolution display 99 is a relatively small display, for example having a diagonal size of a few centimeters, that can be disposed in a head-mounted display. However, users viewing near-to-eye head-mounted displays have a high expectation for display resolution and image quality. In certain embodiments, micro-transfer printed micro-LEDs 50 having a size, for example, of ten or 20 microns in a dimension are used in a high-resolution micro-display.

[0064] For example, in some embodiments, a high-resolution display 99 has a pixel separation of 50 microns for a native resolution of 20 pixels per millimeter. In some embodiments, a high-resolution display 99 has a pixel separation of 25 microns and an effective resolution of 40 pixels per millimeter in both row and column directions. If such a display is used with a 4×4 dither pattern to display an image with four times as many image pixels as display pixels 20 on the display substrate 10 in each dimension, the entire image can be displayed in 16 time periods with an effective resolution of 80 pixels per millimeter, an extremely high resolution.

[0065] In some embodiments of the present invention, as illustrated in FIG. 6, display pixels 20 include a pixel controller 24, for example a small integrated circuit that provides active-matrix control to a display pixel 20. A pixel controller 24 can digitally control micro-LEDs 50 with a pulse width modulation scheme and can be addressed using an active-matrix control method from the display controller

**30** (which can include, for example, separate row and column drivers). In some embodiments, a display controller **30** and pixel controller **24** together with micro-LEDs **50** can load rows of data at a rate greater than 50 MHz per bit. In some embodiments, rows of eight-bit pixel values can be loaded into the display at 6 MHz. For example, in a display with 640 columns x 480 rows, such a loading rate enables a native frame rate of 12500 frames per second. Using a 4x4 dither pattern, a high-resolution display **99** can operate at one sixteenth that rate or 781 frames per second, well above the required 30 frames per second to avoid flicker. For an image having 1080 rows (such as in, for example, a standard high-definition television) and using a 4x4 dither pattern, thereby achieving an effective 8 kx4 k display resolution, the frame rate is 347 frames per second. Even a 16 kx8 k resolution is readily achievable.

**[0066]** In some embodiments, it is not only necessary to provide data at a rate sufficient to avoid flicker, it is necessary to move a display substrate **10** to a number of positions to display the data at a corresponding rate. For example, a display using a 4x4 dither pattern moves a display substrate to 16 locations to display a single image (e.g., frame of a video). In some embodiments, an actuator **40** moves a display substrate **10** a distance up to the pixel separation distance  $D$ , for example up to 50 microns. Commercially available piezoelectric actuators **40** can move distances of a millimeter without difficulty at a rate of 350 mm per second (i.e., one micron in 2.86 microseconds). For example, a high-resolution display **99** with a 50-micron pixel separation distance  $D$  using a commercially available piezoelectric actuator capable of 350 mm per second movement and a 4x4 dither pattern requires a maximum movement in each dimension of movement (e.g., x- and y-dimensions) of 37.5 microns, which takes 107 microseconds (i.e., can occur at a rate of 9324 movements per second) using. Sixteen movements (e.g., one to each position of the 4x4 pattern) would therefore require at most about 1712 microseconds and yield a frame rate limited by the piezoelectric actuators **40** of about 584 frames per second. Thus, a piezoelectric actuator **40** can enable useful frame rates. Micro-LED displays having pixel separation distances  $D$  less than 100 microns have been built and in accordance with some embodiments using a 4x4 spatial dither pattern can operate at 292 frames per second. Thus, some embodiments of the present invention provide a useful high-resolution display **99**.

**[0067]** In some embodiments, display pixels **20** are color pixels having two or more light-emitting sub-pixels and a display controller **30** controls the sub-pixels to emit light of different colors. Referring to FIGS. 1 and 5, in some embodiments, display pixels **20** include red, green, and blue colored sub-pixels, **20R**, **20G**, **20B**. In some embodiments, a color display requires three times as much data communication (i.e., due to the presence of three subpixels per pixel) which reduces the frame rate. However, in an analogous high-resolution display **99** as the example given above, the frame rate remains about 100 frames per second, still well above the threshold necessary to avoid image display flicker.

**[0068]** To ensure that image pixels are displayed at correct locations in a high-resolution display **99** in accordance with some embodiments of the present invention, the location of display pixels **20** at a time can correspond to the relative location of the image pixels in the image displayed by the

display pixels **20**. That is, the locations moved to by the display pixels **20** in the display **99** correspond to discrete locations of image pixels in an image being displayed. Therefore, in some embodiments, the total number of display pixel spatial locations is the same as the number of image pixels in an image being displayed (e.g., as illustrated in FIG. 3), wherein only a subset of the image pixels are instantaneously displayed at a particular time.

**[0069]** In some embodiments, and as illustrated in the figures, spatial locations are interpolated in two dimensions (e.g., using a two-dimensional dither pattern). In some embodiments, spatial locations are interpolated in only one dimension (e.g., using a one-dimensional dither pattern).

**[0070]** Image pixels in a dither pattern can be displayed in any order (e.g., an arbitrary order). In some embodiments, the number of display substrate **10** movements are reduced by displaying image pixels adjacent in one dimension at successive times. For example, with reference to FIG. 3, a display substrate **10** can be moved from position  $P_{00}$  to  $P_{10}$  to  $P_{01}$  to  $P_{00}$ , so that the display substrate **10** only moves the smallest distance possible for each movement, thus keeping each movement time as short as possible. In some embodiments, all movements are to spatially adjacent locations except one, so that only some of the spatial locations at successive times are adjacent. For example, a one-dimensional dither pattern can be used, wherein each movement moves to a spatially adjacent location progressively further away from an initial position except for a movement to reset a display substrate **10** to the initial position. In some embodiments, a large movement (e.g., relative to the size of movement to spatially adjacent locations) is used a limited number of times (e.g., once per image frame) and overlaps with the time needed to load a new image frame into a display controller **30**. Time available for loading scales with magnitude of the large movement (i.e., a larger movement takes a longer time to move). Therefore, moving a display substrate **10** to spatially adjacent locations can reduce time and energy needed to move the display substrate **10**, can improve high-resolution display **99** efficiency, and can increase the display frame rate, thereby reducing flicker. In some embodiments, only some movements are to spatially adjacent locations. For example, with reference to FIG. 3, a display substrate **10** can be moved from  $P_{00}$  to  $P_{10}$  to  $P_{01}$  to  $P_{11}$  to  $P_{00}$  from the diagonally opposite corner of the dither pattern to the initial  $P_{00}$  position. The larger spatial movement from  $P_{11}$  to  $P_{00}$  can allow time for a new image frame to be loaded into a display controller **30**. In some embodiments, multiple movements (interpolations) along a dither pattern are to non-adjacent spatial locations.

**[0071]** Five different exemplary dither patterns are illustrated in FIG. 7. In the first exemplary dither pattern, four-location dither pattern A, display pixels **20** on a display substrate **10** are moved from an upper-left spatial location  $P_{00}$ , to an upper right spatial location  $P_{10}$ , to a lower-right spatial location  $P_{11}$ , to a lower-left spatial location  $P_{01}$ , and then returns to the original, upper-left spatial location  $P_{00}$  at successive times (as shown in FIGS. 2A-2D). The spatial locations of the display pixels **20** at successive times are adjacent.

**[0072]** In the second exemplary dither pattern, nine-location dither pattern B, display pixels **20** on a display substrate **10** are moved from an upper-left spatial location in the horizontal direction to an upper right spatial location and

then down to a middle row of spatial locations. The display pixels **20** then move back to the first column, then down to the bottom row and across to the right side of the 3×3 array of spatial locations, and then back to the original spatial location. Spatial locations at successive times are adjacent except for the return to the original spatial location.

**[0073]** In the third exemplary dither pattern, nine-location dither pattern C, display pixels **20** on a display substrate **10** are moved from an upper-left spatial location in the horizontal direction to an upper right spatial location and then down the right-side column of spatial locations to the bottom row of spatial locations. The display pixels **20** then move back to the first column, then up to the middle row, over to the middle column, and then diagonally back to the original spatial location. In this exemplary 3×3 dither pattern, spatial locations at successive times are all adjacent except for the return to the original spatial location.

**[0074]** In the fourth exemplary dither pattern, sixteen-location dither pattern D, display pixels **20** on a display substrate **10** are moved from an upper-left spatial location in the horizontal direction to an upper right spatial location and then down the right-side column of spatial locations to the bottom row of spatial locations. The display pixels **20** then move back one column, then up to the second row, over another column, and then back to the bottom row of spatial locations. The display pixels **20** then move back to the first column and then to the original spatial location. In this exemplary 4×4 dithered pattern, spatial locations at successive times are all adjacent.

**[0075]** In the fifth exemplary dither pattern, twenty-five-location dither pattern E, display pixels **20** on a display substrate **10** are moved from an upper-left spatial location in the horizontal direction to an upper right spatial location and then down the right-side column of spatial locations to the bottom row of spatial locations. The display pixels **20** then move left one column, up to the second row, left another column, down to the bottom row, and then back and forth up to the original spatial location with alternating row and column movements. In this exemplary 5×5 dither pattern, spatial locations at successive times are all adjacent except for the return to the original spatial location.

**[0076]** The dither patterns of FIG. 7 define rectilinear arrays of display pixel locations. In some embodiments of the present invention, dither patterns can have other shapes, for example diamond shapes, circular shapes, or sinusoidal shapes. Referring to the FIG. 8, patterns A and B, display pixels **20** are spatially interpolated over time to form a diamond pattern alphabetically labeled in the order in which the interpolation occurs ( $P_A, P_B, P_C, P_D$ ). In pattern C, two adjacent diamond patterns are formed in the order ( $P_A, P_B, P_C, P_D, P_E, P_F, P_G, P_H$ ), with the central location ( $P_C, P_G$ ), repeated. Motion of display pixels **20** need not be straight lines as in FIG. 8 pattern A. As shown in FIG. 8 patterns B and C, the display pixels **20** can trace out a circular pattern or a sinusoidal pattern (not shown). Thus, in some embodiments of the present invention, piezo actuators move a display substrate in all or a part of a straight line segment, a curved line segment, a circular line segment, a circle, a sinusoidal line segment, or a sine wave.

**[0077]** In some embodiments of the present invention, and as illustrated in FIG. 9, each display pixel **20** on a display substrate **10** is a single-color display pixel **20** and adjacent display pixels **20** are different single-color display pixels **20** (i.e., that each emit a different single color). The display

substrate **10** then moves a distance at least equal to the separation distance  $D$  to display different colors at the different pixel display locations. Hence, in such embodiments, a display **99** is a color sequential high-resolution display **99**, but each different color is out of phase with the other colors at different neighboring spatial locations. Such a display can display an image in accordance with the exemplary method shown in FIG. 4. For example, with reference to FIG. 9, at time  $0$  ( $T_0$ ) the first display pixel **20R** emits red light at a first spatial location, the second display pixel **20G** at a second spatial location adjacent to the first spatial location emits green light, and the third display pixel **20B** adjacent to the second spatial location emits blue light. At a successive time  $T_1$ , the display substrate **10** is moved so that each of the single-color display pixels **20** is moved to an adjacent spatial location so that red display pixel **20R** is moved to the second spatial location and emits red light, green display pixel **20G** is moved to the third spatial location and emits green light, and blue display pixel **20B** is moved to a fourth spatial location to emit blue light. At a second successive time  $T_2$ , the display substrate **10** is moved so that each of the single-color display pixels **20** is moved to another adjacent spatial location so that red display pixel **20R** is moved to the third spatial location and emits red light, green display pixel **20G** is moved to the fourth spatial location and emits green light, and blue display pixel **20B** is moved to a fifth spatial location and emits blue light. The display substrate **10** is then moved back to its original position and the process is repeated for a second image frame. Thus, at the first spatial location red light is emitted, then green light, then blue light, corresponding to the different colors of the image pixel at the first spatial location. At the second spatial location green light is emitted, then red light, then blue light, corresponding to the different colors of the image pixel at the second spatial location. At the third spatial location blue light is emitted, then green light, then red light, corresponding to the different colors of the image pixel at the third spatial location.

**[0078]** Referring to FIG. 10, a similar process as described above can be used for a two-dimensional dither pattern if the dither pattern is arranged so that each color is emitted at each spatial location, for example by locating different single-color display pixels **20** spatially out of phase in adjacent rows (or columns) of the high-resolution display **99**. As shown in FIG. 10, the display pixels **20** on the display substrate **10** first emit light at the initial spatial location at time  $T_0$ , then move to the right to emit light at the first spatial location at time  $T_1$ , then move down to emit light at the second spatial location at time  $T_2$ , then move back to the initial spatial location at time  $T_3$ , so that a different color of light is sequentially emitted at each spatial location. Alternatively, the display pixels **20** on the display substrate **10** can move left at time  $T_3$  and emit light in the fourth spatial location and then return to the initial spatial location. Such a process will order the colors at each spatial location differently for successive time frames.

**[0079]** In some embodiments of the present invention, spatial locations between single-color display pixels **20** can also be interpolated in one or two dimensions (e.g., in accordance with FIGS. 2A-2D), to further increase the resolution of a high-resolution display **99**.

**[0080]** Referring to FIG. 11, in some embodiments of the present invention, an actuator **40** is located beneath (or above) a display substrate **10** to provide motion in the  $z$



direction orthogonally to the surface of the display substrate **10** on which an array of light-emitting display pixels **20** are disposed. In some embodiments, a three-dimensional image can be represented by emitting light at different depth directions at different times.

**[0081]** In some embodiments, if actuators **40** are controlled by a display controller **30** to operate out of phase, a surface of a display substrate **10** can be oriented in different directions (tilted). In some embodiments, if display pixels **20** comprise light-emitting lasers, for example laser diodes, then light can be emitted in different directions, for example providing different images to different viewers or to the different eyes of a single viewer.

**[0082]** In some embodiments of the present invention, piezo actuators move a display substrate in a resonant mechanical mode in one or both of a horizontal plane parallel to or a vertical plane orthogonal to a surface of the display substrate on which an array of light-emitting display pixels are disposed. Resonant mechanical motion at resonant frequencies of a display substrate **10** can enable a reduced power and a higher frame rate of display substrate **20** motion. Furthermore, in some embodiments, a display substrate **10** is tilted by operating actuators **40** out of phase or by providing actuators **40** at only some of the sides or edges of a display substrate **10**, the display substrate itself can vibrate, bending in response to actuator **40** mechanical impulse. Vibration can be mechanically resonant and can cause display pixels **20** to emit light in different directions over time, reducing brightness in one direction while increasing the volume of space into which light is emitted by the display pixels **20**.

**[0083]** Referring to FIG. 12, in some embodiments of the present invention, a high-resolution display **99** comprises an optical structure **70** disposed in combination with an array of display pixels **20** so that light emitted by the display pixels **20** is optically processed by the optical structure **70** and piezo actuators **40** move the display substrate **10** relative to the optical structure **70**. The optical structure **70** can have its own actuators **40** or not (as shown). An optical structure **70** can be any one or more of a variety of optical elements, for example a lenslet array having a lenslet **72** disposed on an optical substrate **76** and disposed in combination with each display pixel **20**, as shown in FIG. 12. In some embodiments, as an actuator moves display pixels **20** relative to the lenslets **72**, light **80** emitted from the display pixels **20** can be optically processed in different ways, for example refracted in different directions.

**[0084]** Referring to FIGS. 13A-13C, in some embodiments, an optical structure is a color-filter array **74** disposed on a transparent optical substrate **76**. In some embodiments, for example, display pixels **20** can be single-emitter pixels that emit white light. As an actuator **40** moves a color-filter array **74** relative to the display pixels **20**, white light emitted from the display pixels is successively processed by filtering the emitted white light with a red (FIG. 13A), green (FIG. 13B), and blue (FIG. 13C) color filter.

**[0085]** Referring to FIG. 14, in some embodiments, a plurality of display substrates **10** can be substantially transparent (within the limits of the materials and manufacturing processes, for example, greater than 50%, 60%, 70%, 80% or 90% transparent) and stacked to form a multi-layer high-resolution display **99**. If the display substrates **10** are controlled by a display controller **30** to locate display pixels **20** in different layers at different locations, light from the

different display pixels **20** can be emitted from each layer at the same time, providing a higher resolution and frame rate, and, if desired, a three-dimensional display. In some embodiments, for example in accordance with FIGS. **10** and **11**, each layer can provide a three-dimensional image at successive times, and the combination of layers at the successive times forms a high-resolution three-dimensional display **99** with an increased depth.

**[0086]** In some embodiments, an actuator **40** never fully stops in a specific position but continues moving as image pixels are displayed. This will blur the displayed pixels but for such short times and distances that the effect is not noticeable.

**[0087]** In some embodiments, using a 2x2 dither pattern, an actuator **40** has a range of motion for moving a display substrate **10** of at least one half of a pixel separation distance **D** in size. In some embodiments, using a 3x3 dither pattern, an actuator **40** has a range of motion for moving a display substrate **10** of at least two thirds of a pixel separation distance **D** in size. In some embodiments, using a 4x4 dither pattern, an actuator **40** has a range of motion for moving a display substrate **10** of at least three quarters of a pixel separation distance **D** or at least the pixel separation distance **D** in size. In some embodiments, an actuator **40** moves a display substrate **10** a distance equal to a pixel separation distance **D** or a distance twice the pixel separation distance **D** (for example if three different single-color display pixels **20** are used).

**[0088]** In some embodiments, in which display pixels **20** include multiple sub-pixels, light-emitting sub-pixels are separated by a distance **P** that is less than or equal to one quarter of the separation distance. In some embodiments, this helps to avoid blur and ensure that sub-pixels are not moved to a location that overlaps a different sub-pixel in a different display pixel **20**.

**[0089]** In some embodiments, as shown in FIG. 15, a high-resolution display **99** includes a head set **60** (for example a head-mounted display with a strap **62** and a visor **64**) to which a display substrate **10** is mounted to make an augmented or virtual reality display. In some embodiments, at least a display substrate, an array of light-emitting display pixels, and at least one actuator are mounted to a head set. In some embodiments, a controller is also mounted to the headset. In some embodiments, a head set **60** includes two high-resolution displays **99**, each comprising an array of light-emitting display pixels **20**.

**[0090]** Micro-LEDs **50** used in high-resolution displays **99** can comprise semiconductor structures such as silicon, or semiconductor structures that are compound semiconductor structures, for example GaN. Different micro-LEDs **50** that emit different colors of light can be made using different semiconductors, such as different compound semiconductors. Micro-LEDs **50** can be inorganic LEDs and can include dielectric materials, for example silicon dioxide or nitride to protect the micro-LEDs **50** and provide tethers **52** (e.g., that can be fractured) for use in transfer printing (e.g., micro-transfer printing). Micro-LEDs **50** having various structures can be made using, for example, doped or undoped semiconductor materials and can be made using photolithographic techniques. A display pixel **20** can comprise one or more inorganic LEDs (iLED) such as micro-LEDs **50**. In some embodiments, solid-state lasers (e.g., diode lasers such as micro diode lasers) are used as light emitters in a display pixel **20**. It is understood that where reference is made to an

LED in a display pixel **20**, a comparably sized diode laser can be used in place of the LED or micro-LED. Micro-LEDs **50** can be relatively small, for example in embodiments each micro-LED **50** has at least one of a width from 2 to 5  $\mu\text{m}$ , 5 to 10  $\mu\text{m}$ , 10 to 20  $\mu\text{m}$ , or 20 to 50  $\mu\text{m}$ , a length from 2 to 5  $\mu\text{m}$ , 5 to 10  $\mu\text{m}$ , 10 to 20  $\mu\text{m}$ , or 20 to 50  $\mu\text{m}$ , and a height from 2 to 5  $\mu\text{m}$ , 4 to 10  $\mu\text{m}$ , 10 to 20  $\mu\text{m}$ , or 20 to 50  $\mu\text{m}$ . In some embodiments, micro-LEDs **50** are formed in substrates or on supports separate, distinct, and independent from a display substrate **10**.

[0091] According to some embodiments of the present invention, display pixels **20** incorporate micro-elements, such as micro-inorganic-light-emitting diodes and micro-controllers (e.g., pixel controllers **24** as shown in FIG. 6) having micron-sized dimensions. In some embodiments, because such micro-elements are so small, they take very little space and have very little mass, such that actuators **40** can reliably and repeatably move a display substrate **10** to form images on a high-resolution display **99**. In some embodiments, small size enables a small aperture ratio (fill factor) of a display substrate **10** and provides space for the different spatial locations between the display pixels **20**. Small mass can enable rapid movement and high frame rates, thereby increasing temporal resolution and reducing image flicker. In some embodiments, small size and mass of micro-controllers in display pixels **20** also enables an active-matrix control structure for a high-resolution display **99**, thereby improving brightness.

[0092] Methods of forming micro-transfer printable structures are described, for example, in the paper *AMOLED Displays using Transfer-Printed Integrated Circuits* (Journal of the Society for Information Display, 2011, DOI #10.1889/JSID19.4.335, 1071-0922/11/1904-0335, pages 335-341) and U.S. Pat. No. 8,889,485, referenced above. For a discussion of micro-transfer printing techniques see, U.S. Pat. Nos. 8,722,458, 7,622,367 and 8,506,867, the disclosure of each of which is hereby incorporated by reference in its entirety. Micro-transfer printing using compound micro-assembly structures and methods can also be used with the present invention, for example, as described in U.S. patent application Ser. No. 14/822,868, filed Aug. 10, 2015, entitled Compound Micro-Assembly Strategies and Devices, which is hereby incorporated by reference in its entirety. In some embodiments, a high-resolution display **99** (e.g., a display substrate **10** thereof) is a compound micro-assembled device. In some embodiments, display pixels **20** are micro-transfer printed onto a display substrate **10** [e.g., wherein the printed display pixels **20** comprise broken (e.g., fractured) tethers resulting from the micro-transfer printing process]. In some embodiments, light emitters such as micro-LEDs or laser diodes are micro-transfer printed onto a display substrate **10** [e.g., wherein the printed light emitters comprise broken (e.g., fractured) tethers resulting from the micro-transfer printing process]. In some embodiments, micro-controllers used in active matrix control of a pixel are micro-transfer printed onto a display substrate **10** [e.g., wherein printed micro-controllers comprise broken (e.g., fractured) tethers resulting from the micro-transfer printing process]. In some embodiments, components such as light emitters and, optionally, micro-controllers are micro-transfer printed onto an intermediate substrate in order to form a display pixel **20**, and the display pixel **20** is then micro-transfer printed onto a display substrate. Additional details useful in some embodiments are described in U.S. patent

application Ser. No. 14/743,981, filed Jun. 18, 2015, entitled Micro Assembled LED Displays and Lighting Elements, the disclosure of which is hereby incorporated by reference in its entirety.

[0093] As is understood by those skilled in the art, the terms “over”, “under”, “above”, “below”, “beneath”, and “on” are relative terms and can be interchanged in reference to different orientations of the layers, elements, and substrates included in the present invention. For example, a first layer on a second layer, in some embodiments means a first layer directly on and in contact with a second layer. In other embodiments, a first layer on a second layer can include another layer there between. Additionally, “on” can mean “on” or “in.”

[0094] Having described certain embodiments, it will now become apparent to one of skill in the art that other embodiments incorporating the concepts of the disclosure may be used. Therefore, the invention should not be limited to the described embodiments, but rather should be limited only by the spirit and scope of the following claims.

[0095] Throughout the description, where apparatus and systems are described as having, including, or comprising specific components, or where processes and methods are described as having, including, or comprising specific steps, it is contemplated that, additionally, there are apparatus, and systems of the disclosed technology that consist essentially of, or consist of, the recited components, and that there are processes and methods according to the disclosed technology that consist essentially of, or consist of, the recited processing steps.

[0096] It should be understood that the order of steps or order for performing certain action is immaterial so long as the disclosed technology remains operable. Moreover, two or more steps or actions in some circumstances can be conducted simultaneously. The invention has been described in detail with particular reference to certain embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

#### PARTS LIST

- [0097] D pixel separation distance
- [0098] P sub-pixel separation distance
- [0099] P<sub>00</sub> position 00
- [0100] P<sub>01</sub> position 01
- [0101] P<sub>10</sub> position 10
- [0102] P<sub>11</sub> position 11
- [0103] P<sub>A</sub>, P<sub>B</sub>, P<sub>C</sub>, P<sub>D</sub>, P<sub>E</sub>, P<sub>F</sub>, P<sub>G</sub>, P<sub>H</sub> display pixel position
- [0104] **10** display substrate
- [0105] **20** display pixel
- [0106] **20R** red pixel/sub-pixel
- [0107] **20G** green pixel/sub-pixel
- [0108] **20B** blue pixel/sub-pixel
- [0109] **22** wires
- [0110] **24** pixel controller
- [0111] **30** display controller
- [0112] **40** actuator
- [0113] **50** inorganic micro-light-emitting diode
- [0114] **52** tether
- [0115] **60** headset
- [0116] **62** strap
- [0117] **64** visor
- [0118] **70** optical structure

[0119] 72 lenslet  
 [0120] 74 color-filter array  
 [0121] 74R red color filter  
 [0122] 74G green color filter  
 [0123] 74B blue color filter  
 [0124] 76 optical substrate  
 [0125] 80 light  
 [0126] 99 high-resolution display  
 [0127] 400 providing display step  
 [0128] 402 initial emitting light step  
 [0129] 404 moving display step  
 [0130] 406 emitting light step  
 [0131] 408 determine progress in dither pattern step  
 [0132] 410 load new image step

What is claimed:

1. A high-resolution display, comprising:  
 a display substrate;  
 an array of light-emitting display pixels disposed on the display substrate;  
 at least one actuator for physically moving the display substrate and the array of light-emitting display pixels to different physical locations in at least one dimension in a direction parallel to a surface of the display substrate;  
 a controller for controlling the light-emitting operation of the display pixels and for controlling a spatial location of the display pixels; and  
 wherein the controller controls the at least one actuator to interpolate the spatial location of the display pixels at successive times and controls the light-emitting operation of the display pixels to display a different subset of image pixels in an image at each successive time, wherein a total number of display pixels in the array of light-emitting display pixels is less than and evenly divides a total number of image pixels in the image in at least one dimension.
2. The high-resolution display of claim 1, wherein the display pixels are color pixels comprising two or more light-emitting sub-pixels and the controller controls the sub-pixels to emit light of different colors.
3. The high-resolution display of claim 1, wherein each spatial location of the display pixels that the controller controls the at least one actuator to move the display substrate to at a successive time of the successive times corresponds to a relative location of image pixels in the image displayed by the display pixels at the successive time.
4. The high-resolution display of claim 1, wherein a total number of spatial locations the controller controls the at least one actuator to move to is the same as the total number of image pixels in the image.
5. The high-resolution display of claim 1, wherein the spatial locations are interpolated in one dimension.
6. The high resolution display of claim 1, wherein the spatial locations are interpolated in two directions.
7. The high-resolution display of claim 6, wherein the two directions are two orthogonal directions.
8. The high-resolution display of claim 1, wherein the spatial locations at successive times correspond to adjacent image pixels in the image.
9. The high-resolution display of claim 1, wherein the controller controls the at least one actuator to move continuously along a dither pattern.
10. The high-resolution display of claim 1, wherein each display pixel is separated from a neighboring pixel by a pixel

separation distance and each of the at least one actuator has a range of motion for moving the display substrate that is at least equal to the pixel separation distance.

11. The high-resolution display of claim 10, wherein each display pixel is a single-color display pixel and adjacent display pixels emit different single-colors of light.

12. The high-resolution display of claim 1, comprising an actuator for physically moving the display substrate and the array of light-emitting display pixels in a direction orthogonal to a surface of the display substrate on which the array of light-emitting display pixels are disposed.

13. The high-resolution display of claim 1, wherein the display substrate is substantially transparent and the high-resolution display comprises at least one additional display substrate each comprising an array of light-emitting display pixels disposed thereon and at least one actuator for physically moving the additional display substrate and the array of light-emitting display pixels disposed thereon to different spatial locations at least one dimension parallel to a surface of the display substrate, wherein the display substrate and the at least one additional display substrate form a stack of display substrates.

14. The high-resolution display of claim 1, wherein each display pixel is separated from a neighboring display pixel by a pixel separation distance and each of the at least one actuator has a range of motion for moving the display substrate of at least one half of the pixel separation distance.

15. The high-resolution display of claim 1, wherein each display pixel is separated from a neighboring pixel by a pixel separation distance, wherein the display pixels are color pixels comprising two or more light-emitting sub-pixels, and the two or more light-emitting sub-pixels in a color pixel are separated by a distance that is less than or equal to one quarter of the pixel separation distance.

16. The high-resolution display of claim 1, wherein the light-emitting pixels comprise inorganic micro-light-emitting diodes comprising at least one of a length, a width, and a thickness that is less than or equal to twenty microns.

17. The high-resolution display of claim 15, wherein each sub-pixel comprises at least one micro-transfer printed micro-light-emitting diode comprising a fractured or separated tether.

18. The high-resolution display of claim 1, wherein each light-emitting display pixel in the array of light-emitting display pixels comprises an active-matrix pixel controller.

19. The high-resolution display of claim 1, wherein the at least one actuator is (i) one or more piezo actuators disposed to move the display substrate in one dimension; (ii) two or more piezo actuators disposed to move the display substrate in two dimensions; or (iii) three or more piezo actuators disposed to move the display substrate in three dimensions.

20. The high-resolution display of claim 1, comprising an optical structure disposed over the array of display pixels such that light emitted by the display pixels is optically processed by the optical structure, wherein the at least one actuator is for moving the display substrate relative to the optical structure.

21. The high-resolution display of claim 20, wherein the at least one actuator moves the display substrate in at least one of (i) at least a portion of a straight line segment, a curved line segment, a circle, a circular line segment, a sinusoidal line segment, a sine wave, and (ii) a resonant mechanical mode in one or both of a horizontal plane

parallel and a vertical plane orthogonal to a surface of the display substrate on which the array of light-emitting display pixels are disposed.

22. The high-resolution display of claim 1, comprising a head set, wherein at least the display substrate, the array of light-emitting display pixels, and the at least one actuator are mounted to the head set.

23. A method of displaying images on a high-resolution display using spatial dithering, wherein the high-resolution display comprises a display substrate, an array of light-emitting display pixels disposed on the display substrate, at least one actuator for physically moving the display substrate and the array of light-emitting display pixels to different physical locations in at least one dimension in a direction parallel to a surface of the display substrate, and a controller for controlling the light-emitting operation of the display pixels and for controlling a spatial location of the display pixels and the method comprises the steps of:

- (a) emitting light from the array of display pixels while the display pixels are in an initial spatial location, wherein the emitted light corresponds to a subset of image pixels of an image and a total number of display pixels in the array of light-emitting display pixels is less than and evenly divides a total number of image pixels in the image in at least one dimension;
- (b) controlling, by the controller, movement of one or more of the at least one actuator to move the display substrate such that the array of display pixels are interpolated to a different spatial location along a dither pattern;
- (c) emitting light from the array of display pixels while the array is in the different spatial location along the dither pattern, wherein the light emitted from the array of display pixels while in the different spatial location corresponds to a different subset of image pixels in the image than the subset of image pixels in the; and
- (d) repeating step (b) and step (c) until light has been emitted from the array of display pixels in each spatial location, thereby displaying the image.

24. The method of claim 23, wherein the dither pattern is a 2x2 pattern, a 3x3 pattern, a 4x4 pattern, or a 5x5 pattern.

25. The method of claim 23, wherein spatial locations are interpolated along the dither pattern in one dimension.

26. The method of claim 23, wherein spatial locations are interpolated along the dither pattern in two directions.

27. The method of claim 26, wherein the two directions are two orthogonal directions.

28. The method of claim 23, wherein each pair of successive spatial locations interpolated along the dither pattern corresponds to adjacent subsets of image pixels in the image.

29. The method of claim 23, wherein at least one pair of successive spatial locations interpolated along the dither pattern corresponds to non-adjacent subsets of image pixels in the image.

30. The method of claim 23, wherein the array of display pixels are interpolated to successive spatial locations along the dither pattern by interpolating along at least a portion of a straight line segment, a curved line segment, a circle, a circular line segment, a sinusoidal line segment, or a sine wave.

31. The method of claim 23, comprising:

loading a second image to be displayed while moving, in response to the controller actuating the at least one actuator, the array of display pixels to the initial spatial position from a non-adjacent spatial location.

32. The method of claim 23, wherein the high-resolution display comprises an orthogonal actuator for physically moving the display substrate and the array of light-emitting display pixels in a direction orthogonal to a surface of the display substrate on which the array of light-emitting display pixels are disposed, and the method comprises:

controlling, by the controller, movement of the orthogonal actuator to move the display substrate such that the array of display pixels are interpolated to an orthogonal spatial location along the dither pattern, wherein the orthogonal spatial location is a spatial location that lies above or below a plane of the initial spatial location.

\* \* \* \* \*

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# 摘要(译)

高分辨率显示器包括具有设置在其上的用于显示包括图像像素阵列的图像的发光显示像素阵列的显示基板。发光显示像素阵列中的显示像素的总数小于并且在至少一个维度上均匀地划分图像中的图像像素的总数。致动器在与显示基板的表面平行的方向上以一维或二维物理移动显示基板和发光显示像素。控制器控制显示像素的发光操作并控制显示像素的物理位置。在一些实施例中，控制器控制致动器以连续时间空间内插显示像素的空间位置，并控制显示像素的发光操作以在每个连续时间显示图像像素的不同子集。

