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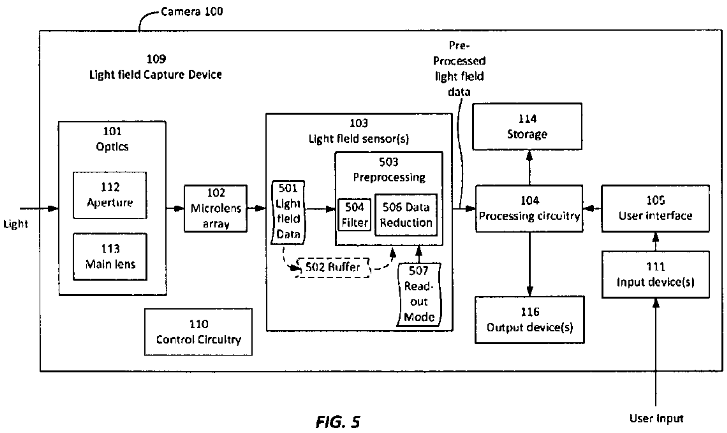

FIG. 5

(57) Abstract: According to various embodiments of the present invention, the optical systems of light field capture devices are optimized so as to improve captured light field image data. Optimizing optical systems of light field capture devices can result in captured light field image data (both still and video) that is cheaper and/or easier to process. Optical systems can be optimized to yield improved quality or resolution when using cheaper processing approaches whose computational costs fit within various processing and/or resource constraints. As such, the optical systems of light field cameras can be optimized to reduce size and/or cost and/or increase the quality of such optical systems.

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OPTIMIZATION OF OPTICAL SYSTEMS FOR IMPROVED LIGHT FIELD CAPTURE AND MANIPULATION

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CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority from U.S. Provisional Application Serial No. 61/644,851 for "Optimization of Optical Systems for Improved Light Field Capture and Manipulation (Atty. Docket No. LYT064-PROV), filed on May 9, 2012, the disclosure of which is incorporated herein by reference in its entirety.

[0002] The present application is related to U.S. Utility Application Serial No. 13/027,946 for "3D Light Field Cameras, Images and Files, and Methods of Using, Operating, Processing and Viewing Same" (Atty. Docket No. LYT3006), filed on February 15, 2011, the disclosure of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0003] The present invention relates to systems and methods for optimizing optical systems for improved capture and manipulation of light field image data.

BACKGROUND

[0004] Light field capture devices, such as, for example, light field still and video cameras, can be used to capture, and optionally process, light field image data. Some light field capture devices can also accept and act upon user input and display or otherwise output images and/or other types of data. Light field capture devices can include a variety of different optical components used to capture light field image data, including sensors (such as CCD or CMOS sensors), microlens arrays, main lenses, and/or lens arrays.

[0005] Light field capture devices may capture light field image data using any suitable method for doing so. One example of such a method includes, without limitation, using a microlens array on top of an image sensor (e.g., a CCD or CMOS sensor) as described in Ng et al., Light field photography with a hand-held plenoptic capture device, Technical Report CSTR 2005-02, Stanford Computer Science. Other examples include the use of a plurality of independently controlled cameras, each with its own lens and sensor, an array of cameras that image onto a single shared sensor, a plenoptic lens, and/or any combination of these.

[0006] In many environments, light field capture devices capture light field image data in the form of highly modulated 4D data that can then be processed to generate 2D and/or 3D output images which can be viewed by a user. Examples of such processing may include (but are not limited to) generating refocused images, parallax views or perspective-shifted images, all-in-focus or extended depth of field (EDOF) images, depth maps, 3D/stereo images, and any combination thereof.

[0007] Such processing of light field image data can be expensive in terms of computational resources, memory bandwidth, and/or power requirements. Thus, in many conventional systems, sacrifices are made in image quality, processing time, resolution, and the like, in order to facilitate light field capture. Users are therefore forced to trade off between the flexibility and capabilities of light field image capture, on the one hand, and high levels of image quality and resolution on the other.

SUMMARY

[0008] According to various embodiments of the present invention, optical systems of light field capture devices are optimized so as to improve captured light field image data. Such improvements can be measured by one or more metrics, including (but not limited to) image quality, processing efficiency, and generated image resolution. According to various embodiments, any of a plurality of methods, systems, and algorithms can be applied in order to process light field image data that has been captured by a light field capture device comprising one or more of the optical system optimizations enumerated herein.

[0009] According to various embodiments, optical systems of light field capture devices are optimized to result in captured light field image data (both still and video) that is cheaper and/or easier to process. For example, in at least one embodiment, optical systems are optimized to yield improved quality or resolution when using cheaper processing approaches whose computational costs fit within various processing and/or resource constraints. As such, the optical systems of light field cameras can be optimized to reduce size and/or cost and/or increase the quality of such optical systems. Such optimizations may be particularly useful in contexts where processing power and/or device size may be limited, such as for example in the context of a mobile device such as a smartphone.

[0010] According to various embodiments, the present invention can include one or more of the following components or aspects, singly or in any suitable combination:

- Modifying the sensor read-out capabilities of digital image sensors that may be used in conjunction with a microlens array to capture light field image data, such that read-out modes are tailored for light field image data capture. In particular, read-out modes that perform a reduction in data size by binning or skipping pixels are optimized to result in less degradation of the light field image data.

- Modifying the sensor's color filter array (CFA) grid layout/pattern based on the disk pattern in the light field image formed on the sensor; this can include, for example, selecting the CFA color of each pixel based on its light field coordinates, as described in more detail below.
- Varying pixel properties such as exposure durations and pixel gains as a function of the pixel's light field coordinates, as defined in more detail below.
- Jittering the positions of pixels on a sensor and/or microlenses in a microlens array.
- Modifying the design of the microlens array and main lens design and placement within the optical system to produce disk images with vertical and/or horizontal pitches of integer numbers of sensor pixels, where the integer pitch is chosen to enable processing approaches that are cheaper, faster, and/or higher quality.
- Modifying the design of the microlens array and main lens to increase the maximum acceptable chief ray angle (CRA) of the optical system.
- Positioning and/or orienting a microlens array on top of a digital image sensor based on the available read-out modes and/or capabilities of the sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The accompanying drawings illustrate several embodiments of the invention and, together with the description, serve to explain the principles of the invention according to the embodiments. One skilled in the art will recognize that the particular embodiments illustrated in the drawings are merely exemplary, and are not intended to limit the scope of the present invention.

[0012] Fig. 1A depicts an example architecture for a light field capture device, according to one embodiment.

[0013] Fig. 1B depicts an example architecture for a light field capture device for implementing the present invention according to one embodiment.

[0014] Fig. 2 depicts a portion of a light field image.

[0015] Fig. 3A depicts transmission of light rays through a microlens to illuminate pixels in a digital sensor.

[0016] Fig. 3B depicts an arrangement of a light field capture device wherein a microlens array is positioned such that images of a main-lens aperture, as projected onto the digital sensor, do not overlap.

[0017] Fig. 4 depicts an example of projection and reconstruction to reduce a 4-D light field representation to a 2-D image.

[0018] Fig. 5 depicts another example architecture of a light field capture device, according to one embodiment.

[0019] Fig. 6 is a flow diagram depicting a method for reducing the size of captured light field image data, according to one embodiment.

[0020] Fig. 7 depicts a portion of a light field image with center rectangles.

[0021] Fig. 8 depicts an example arrangement of photodiodes for a read-out mode that skips pixels that are near or on the edge between light field disk images, according to one embodiment.

[0022] Fig. 9 depicts another example architecture of a light field capture device, according to one embodiment.

[0023] Fig. 10 is a flow diagram depicting a method for modifying a color filter array (CFA) to improve the quality of color information captured from the light field, according to one embodiment.

[0024] Fig. 11 depicts another example architecture of a light field capture device, according to one embodiment.

[0025] Fig. 12 is a flow diagram depicting a method for modifying pixel properties, according to one embodiment.

[0026] Fig. 13 depicts another example architecture of a light field capture device, according to one embodiment.

[0027] Fig. 14 is a flow diagram depicting a method for introducing jitter into optical system components, according to one embodiment.

[0028] Figs. 15 and 16 are examples of transposing light field data, according to one embodiment.

[0029] Fig. 17A is an example of an optical system.

[0030] Fig. 17B is an example of a light field image having disks.

[0031] Fig. 17C is an example of a sub-sampling pattern for a light field image.

[0032] Fig. 17D is an example of transposing a subsampled portion of a light field image.

[0033] Fig. 18A is an example of an optical system.

[0034] Fig. 18B is an example of a light field image having disks.

[0035] Fig. 18C is an example of a sub-sampling pattern for a light field image.

[0036] Fig. 18D is an example of transposing a subsampled portion of a light field image.

[0037] Fig. 19 is a flow diagram depicting a method for determining and configuring a microlens array for use in a light field image capture device, according to one embodiment.

[0038] Fig. 20 depicts top-down views of two example microlens arrays.

[0039] Fig. 21 is an example 3D plot of the surfaces in Fig. 20.

[0040] Fig. 22 depicts an example 2D slice through a microlens array of tilted microlenses.

[0041] Figs. 23A and 23B depict two examples of different types of optimization of the tilted MLA side wall angle.

DETAILED DESCRIPTION

[0042] For purposes of the description provided herein, the following definitions are used:

- capture: can refer to either or both of still capture or video capture.
- image: a two-dimensional array of pixel values, or pixels, each specifying a color.
- light field image: an image that contains a representation of light field image data captured at the sensor.

- microlens: a small lens, typically one in an array of similar microlenses.
- color filter array (CFA): a mosaic of color filters placed over the pixel sensors of an image sensor to capture color information.

[0043] Optical systems are defined herein to encompass any or all components of the optical path of any suitable light field capture device, including any sensors (such as CCD or CMOS sensors), microlens arrays, main lenses, and/or lens arrays.

[0044] Light field capture devices are defined herein as any devices that are capable of capturing light field image data, optionally processing light field image data, optionally accepting and acting upon user input, and optionally displaying or otherwise outputting images and/or other types of data. Examples of light field capture devices include (but are not limited to) light field still and video cameras.

[0045] In addition, for ease of nomenclature, the term "camera" is used herein to refer to an image capture device or other image data acquisition device. Such a data acquisition device can be any device or system for acquiring, recording, measuring, estimating, determining and/or computing data representative of a scene, including but not limited to two-dimensional image data, three-dimensional image data, and/or light field image data. Such a data acquisition device may include optics, sensors, and image processing electronics for acquiring data representative of a scene, using techniques that are well known in the art. One skilled in the art will recognize that many types of data acquisition devices can be used in connection with the present invention, and that the invention is not limited to cameras. Thus, the use of the term "camera" herein is intended to be illustrative and exemplary, but should not be considered to limit the scope of the invention. Specifically, any use of such term herein should be considered to refer to any suitable device for acquiring image data.

[0046] In the following description, several techniques and methods for optimizing optical systems for improved light field capture and manipulation are described. One skilled in the art will recognize that these various techniques and methods can be performed singly and/or in any suitable combination with one another.

Architecture

[0047] In at least one embodiment, the system and method described herein can be implemented in connection with light field images captured by light field capture devices including but not limited to those described in Ng et al., Light field photography with a hand-held plenoptic capture device, Technical Report CSTR 2005-02, Stanford Computer Science. Referring now to Fig. 1A, there is shown a block diagram depicting an architecture for implementing the present invention in a light field camera 100, according to one embodiment. Examples of light field camera 100 include (but are not limited to) light field still and video cameras. One skilled in the art will recognize that the particular configuration shown in Fig. 1A is merely exemplary, and that other architectures are possible for light field camera 100. One skilled in the art will further recognize that several of the components shown in the configuration of Fig. 1A are optional, and may be omitted or reconfigured.

[0048] As shown, light field camera 100 is one example of a light field capture device 109; for ease of nomenclature, the terms are used interchangeably, although any suitable light field capture device 109 can be used in place of camera 100. Light field capture device 109 includes optics 101, microlens array 102, and image sensor 103 (including a plurality of individual sensors for capturing pixels). Optics 101 may include, for example, aperture 112 for allowing a selectable amount of light into light field camera 100, and main lens 113 for focusing light toward microlens array 102. In at least one embodiment, microlens array 102 may be disposed and/or incorporated in the optical path of camera 100 (between main lens 113 and sensor 103) so as to facilitate acquisition, capture, sampling of, recording, and/or obtaining light field image data via sensor 103. Referring momentarily to Fig. 1B, there is shown an example of an architecture for a light field camera 100 for implementing the present invention according to one embodiment. The Figure is not shown to scale. Fig. 1B shows, in conceptual form, the relationship between aperture 112, main lens 113, microlens array 102, and sensor(s) 103, as such components interact to capture light field image data for subject 117.

[0049] Referring again to Fig. 1A, light field image data from sensor(s) 103 can be processed by processing circuitry 104, and presented as output on output device(s) 116. In at least one embodiment, the output presented at output device(s) 116 can be 2D images or projections of light field image data, as generated by processing circuitry 104.

[0050] In at least one embodiment, light field camera 100 may also include control circuitry 110 for facilitating acquisition, sampling, recording, and/or obtaining light field image data. For example, control circuitry 110 may manage and/or control (automatically or in response to user input) the acquisition timing, rate of acquisition, sampling, capturing, recording, and/or obtaining of light field image data.

[0051] In at least one embodiment, captured light field image data is provided to processing circuitry 104. Processing circuitry 104 may be disposed in or integrated into light field capture device 109 (as shown in Fig. 1A), or it may be in a separate component external to light field capture device 109. Such separate component may be local or remote with respect to light field image capture device 109. Any suitable wired or wireless protocol can be used for transmitting light field image data to circuitry 104; for example device 109 can transmit light field image data and/or other data via the Internet, a cellular data network, a WiFi network, a BlueTooth communication protocol, and/or any other suitable means.

[0052] Generally, processing circuitry 104 operates on light field image data received from light field sensor(s) 103, to generate any output, such as, for example, still images, 2D video streams, and the like. In various embodiments, processing circuitry 104 can use any suitable method of generating still images, 2D images, and the like from light field image data, including (but not limited to) those described below and in related cross-referenced applications.

[0053] In at least one embodiment, light field camera 100 may also include a user interface 105 allowing a user to provide user input for controlling the operation of camera 100 for capturing, acquiring, storing, and/or processing image data. In at least one embodiment, user preferences may also be used, as specified by the user in a preferences screen, or as provided based on defaults. User input can be provided to user interface 105 via any suitable user input device(s) 111 such as a touchscreen, buttons, keyboard, pointing device, and/or the like. As such, input received at input device(s) 111 can be used to control and/or configure either of processing circuitry 104 and control circuitry 110.

[0054] In at least one embodiment, camera 100 includes one or more storage device(s) 114, such as memory for storing image data output from light field sensor(s) (and potentially processed by processing circuitry 104). The memory can include external and/or internal memory. In at least one embodiment, the memory can be provided at a separate device and/or location from camera 100.

[0055] For example, camera 100 may store raw light field image data, as output by sensor 103, and/or a representation thereof, such as a compressed image data file. In addition, as described in related U.S. Utility Application Serial No. 12/703,367 for "Light field Camera Image, File and Configuration Data, and Method of Using, Storing and Communicating Same," (Atty. Docket No. LYT3003), filed February 10, 2010, the memory can also store data representing the characteristics, parameters, and/or configurations (collectively "configuration data") of device 109.

Overview

[0056] Light field images often include a plurality of projections (which may be circular or of other shapes) of aperture 112 of camera 100, each projection taken from a different vantage point on camera's 100 focal plane. The light field image may be captured on sensor 103. The interposition of microlens array 102 between main lens 113 and sensor 103 causes images of aperture 112 to be formed on sensor 103, each microlens in array 102 projecting a small image of main-lens aperture 112 onto sensor 103. These aperture-shaped projections are referred to herein as disks, although they need not be circular in shape.

[0057] Light field images include four dimensions of information describing light rays impinging on the focal plane of camera 100 (or other capture device). Two spatial dimensions (herein referred to as x and y) are represented by the disks themselves. For example, the spatial resolution of a light field image with 120,000 disks, arranged in a Cartesian pattern 400 wide and 300 high, is 400×300. Two angular dimensions (herein referred to as u and v) are represented as the pixels within an individual disk. For example, the angular resolution of a light field image with 100 pixels within each disk, arranged as a 10×10 Cartesian pattern, is 10×10. This light field image has a 4-D (x,y,u,v) resolution of (400,300,10,10). Referring now to Fig. 2, there is shown an example of a 2-disk by 2-disk portion of such a light field image 200, including depictions of disks 201 and individual pixels 203; for illustrative purposes, each disk 201 is ten pixels 203 across.

[0058] Accordingly, an image formed on sensor 103 of light field capture device 109 includes a set of small images, referred to as "disk images" (though they need not be circular in shape), which encode a set of 4D light field image data. Each pixel 203 on sensor 103 may be interpreted as corresponding to a particular 4D light field coordinate, where two dimensions specify its spatial position on the sensor, and two dimensions specify the angular or directional information of light that is incident upon that pixel 203. The 2D directional information is encoded by the 2D position of pixel 203 within the disk image of which it is a member.

[0059] Many light rays in the light field within a light field camera contribute to the illumination of a single pixel 203. Referring now to Fig. 3A, there is shown an example of transmission of light rays 202, including representative rays 202A, 202D, through microlens 201B of array 102, to illuminate sensor pixels 203A, 203B in sensor 103.

[0060] In the example of Fig. 3A, solid rays 202A, 202B, 202C illuminate sensor pixel 203A, while dashed rays 202D, 202E, 202F illuminate sensor pixel 203B. The value at each sensor pixel 203 is determined by the sum of the irradiance of all rays 202 that illuminate it. For illustrative and descriptive purposes, however, it may be useful to identify a single geometric ray 202 with each sensor pixel 203. That ray 202 may be chosen to be representative of all the rays 202 that illuminate that sensor pixel 203, and is therefore referred to herein as a representative ray 202. Such representative rays 202 may be chosen as those that pass through the center of a particular microlens 201, and that illuminate the center of a particular sensor pixel 203. In the example of Fig. 3A, rays 202A and 202D are depicted as representative rays; both rays 202A, 202D pass through the center of microlens 201B, with ray 202A representing all rays 202 that illuminate sensor pixel 203A and ray 202D representing all rays 202 that illuminate sensor pixel 203B.

[0061] There may be a one-to-one relationship between sensor pixels 203 and their representative rays 202. This relationship may be enforced by arranging the (apparent) size and position of main-lens aperture 112, relative to microlens array 102, such that images of aperture 112, as projected onto sensor 103, do not overlap. Referring now to Fig. 3B, there is shown an example of an arrangement of a light field capture device, such as camera 100, wherein microlens array 102 is positioned such that images of a main-lens aperture 112, as projected onto sensor 103, do not overlap. The rays 202 depicted in Fig. 3B are representative rays 202, as they all pass through the center of one of microlenses 201 to the center of a pixel 203 of light field sensor 803.

[0062] In at least one embodiment, the 4-D light field representation may be reduced to a 2-D image through a process of projection and reconstruction. Referring now to Fig. 4, there is shown an example of such a process. A virtual projection surface 401 may be introduced, and the intersection of each representative ray 202 with projection surface 401 is computed. Projection surface 401 may be planar or non-planar. If planar, it may be parallel to microlens array 102 and sensor 103, or it may not be parallel. In general, projection surface 401 may be positioned at any arbitrary location with respect to microlens array 102 and sensor 103. The color of each representative ray 202 may be taken to be equal to the color of its corresponding pixel 203. In at least one embodiment, pixels 203 of sensor 103 may include filters arranged in a regular pattern, such as a Bayer pattern, and converted to full-color pixels. Such conversion can take place prior to projection, so that projected rays 202 can be reconstructed without differentiation. Alternatively, separate reconstruction can be performed for each color channel.

[0063] The color of an image pixel 402 on projection surface 401 may be computed by summing the colors of representative rays 202 that intersect projection surface 401 within the domain of that image pixel 402. The domain may be within the boundary of the image pixel 402, or may extend beyond the boundary of the image pixel 402. The summation may be weighted, such that different representative rays 202 contribute different fractions to the sum. Ray weights may be assigned, for example, as a function of the location of the intersection between ray 202 and projection surface 401, relative to the center of a particular pixel 402. Any suitable weighting algorithm can be used, including for example a bilinear weighting algorithm, a bicubic weighting algorithm and/or a Gaussian weighting algorithm.

[0064] During projection to a refocused 2-D image, representative rays 202 are intersected with virtual projection surface 401 that is parallel to microlens array 102, but displaced from it. If virtual projection surface 401 is ahead of microlens array 102 (nearer to the scene), then the reconstructed 2-D image is focused at a virtual projection surface 401 that is ahead of the best focus scene plane of the light field camera 100. (It is farther from the light field camera 100.) Likewise, if virtual projection surface 401 is behind microlens array 102 (farther from the scene) then the reconstructed 2-D image is focused at a virtual projection surface 401 that is behind the best-focus scene plane of the light field camera 100. Objects in the scene whose scene depths correspond to the image depth of virtual projection surface 401 are in essentially exact focus; other objects in the scene are projected with blur that increases with their displacement from that scene depth.

[0065] A depth map is a set of image-side points (points on the image side of main lens 113), each of which corresponds to a visible point in the scene. A point in the scene is visible if light emitted from it reaches the anterior nodal point of main lens 113, either directly or by being reflected from a highly specular surface. The correspondence is such that light emitted from the scene point would be in best focus by main lens 113 at the corresponding image-side point.

[0066] The position of an image-side point in a depth map may be specified in Cartesian coordinates, with x and y indicating position as projected onto light field sensor(s) 103 (x positive to the right, y positive up, when viewing toward the scene along the optical axis of main lens 113), and depth d indicating perpendicular distance from the surface of microlens array 102 (positive toward the scene, negative away from the scene). The units of x and y may be pixels 203—the pixel pitch of sensor 103. The units of d may be lambdas, where a distance of one lambda corresponds to the distance along which a cone of light from any scene point changes its diameter by a value equal to the pitch of microlens array 102. (The pitch of microlens array 102 is the average distance between the centers of adjacent microlenses 201.)

[0067] Thus, for scene-side points that are directly visible to main lens 113, points at scene depths on the plane of the optical focus correspond to an image depth at the (microlens) surface. Points at scene depths that are farther from light field camera 100 than the plane of best focus correspond to points with image depths that are closer to main lens 113 than the plane of best focus. As such, points at scene depths that are farther from light field camera 100 than the plane of best focus have positive depth values. Points at scene depths that are nearer to camera 100 than the plane of best focus correspond to points with image depths that are farther from main lens 113 than the plane of best focus. As such, points at scene depths that are nearer to camera 100 than the plane of best focus have negative depth values.

[0068] According to various embodiments of the present invention, any number of modifications can be performed in order to optimize optical systems of light field capture devices 109 to improve captured light field image data. Examples of such modifications are described herein. One skilled in the art will recognize that these modifications can be applied singly or in any suitable combination.

Sensor Read-out Modifications

[0069] According to at least one embodiment, the sensor read-out capabilities of digital image sensors, for example, light field sensors 103, are modified. Sensor read-out modifications can be used in conjunction with a microlens array, for example, microlens array 102, to capture light field image data, such that the sensor's read-out modes are tailored for light field image data capture. The read-out modes are optimized to result in less degradation of light field image data. A number of different read-out modifications are listed herein; however, this list is exemplary. Any or all of these modifications can be applied singly or in any suitable combination.

[0070] Referring now to Fig. 5, there is shown another example architecture of a light field capture device 109 according to one embodiment. As depicted in Fig. 5, light field sensors 103 include buffer 502 and preprocessing 503. Preprocessing 503 further includes filter 504 and data reduction 506. Generally, light field sensors 103 can capture light field image data 501 from the output of microlens array 102 (e.g., as described in connection with Figs. 1A through 4). Some or all of light field image data 501 can be buffered in buffer 502 and/or sent to preprocessing 503.

[0071] Preprocessing 503 can process light field image data 501 in accordance with read-out mode 507 to reduce the data size of the captured light field image data without any appreciable degradation. Preprocessing 503 can output pre-processed light field image data to processing circuitry 104 for further processor, for example, to generate a 2D image.

[0072] In at least one embodiment, filter 504 filters light field image data 501 to reduce the size of light field image data 501. Filtered light field image data can be stored in buffer 502. Data reduction 506 can access light field image data 501 and/or can access filtered light field image data from buffer 502. Data reduction 506 can implement one or more mechanisms to reduce the size of light field image data. In some embodiments, data reduction 506 uses one of or more of: skipping pixels 203, binning pixels 203, sub-sampling pixels 203, resampling pixels 203, per-pixel operations, per-pixel values, bitmasks, bitmask tiles, weight image tiles, bit depth modifications, pixel maximums, lookup tables, multi-pass read outs, light field aware processing, and sensors with interlaced scan to reduce the size of light- field data.

[0073] Referring now to Fig. 6, there is shown a flow diagram depicting a method for reducing the size of captured light field image data. The method of Fig. 6 will be described with respect to the components and data in Fig. 5.

[0074] In at least one embodiment, one or more light field sensors 103 capture 601 light field image data 501 from the output of microlens array 102. The captured light field image data 501 is pre-processed 602 at the one or more light field sensors 103 in accordance with a specified read-out mode to reduce the data size of the captured light field image data. For example, preprocessing 503 can process light field image data 501 in accordance with read-out mode 507 to reduce the size of light field image data 501. The pre-processed captured light field image data is then sent 603 to processing circuitry 104.

Pre-filtering the sensor image data

[0075] In at least one embodiment, image data 501 is filtered prior to being read out of sensor 103. When a sub-sampled, binned, or resampled read-out mode is utilized, the filtering can occur prior to the sub-sampling, binning, or resampling. For example, one read-out mode may involve skipping columns, and a horizontal filter may be applied to the sensor data prior to this skipping.

[0076] In general, filtering can be horizontal, vertical, or two-dimensional. Two-dimensional filters may or may not be separable. Filtering may be implemented as a straightforward convolution of the image data with a provided mask. In at least one embodiment, filtering may be applied amongst pixels 203 of the same color. For example, in at least one embodiment, same-color filtering can be used for an image sensor in which different pixels 203 represent different colors (e.g., a sensor using a color-filter-array (CFA) such as a Bayer sensor), Alternatively, filtering of such an image may be implemented to consider pixels 203 from multiple colors, for example within a demosaicing algorithm.

[0077] Filtering can be implemented using a small amount of memory on the sensor itself to buffer rows as they are read from the array of pixels 203; such buffering of rows can be performed according to known techniques. Filtering operations may be applied to these buffered rows, and in the case of a vertical or two-dimensional filter, the number of buffered rows may need to be at least as large as the number of taps of the filter in the vertical dimension.

[0078] Once the data is filtered in a local buffer (such as buffer 502), subsequent operations including (but not limited to) sub-sampling, binning, or resampling may be applied, before the data is finally output from sensor 103.

[0079] One advantage of such a sensor capability is to pre-filter (possibly highly) modulated light field image data prior to it being sub-sampled, for example when the sensor image is being sub-sampled and scaled to fit an LCD screen for on-camera live-view operation. Sub-sampling and then downscaling the highly modulated light field image data without a sufficiently large pre-filtering operation may result in unattractive artifacts in the final image due to aliasing patterns.

[0080] The filtering may be spatially varying, or it may be uniform across the whole light field image. In the case of a spatially varying filter, the variations may be a function of the light field coordinates of the pixels 203 that are being filtered; such an approach can be used to apply larger filtering (and hence greater amounts of pixel aggregation) in highly modulated regions of the light field image.

Skipping pixels based on their light field coordinates

[0081] In at least one embodiment, sensor read-out modes can skip pixels 203 based on their light field coordinates, rather than skipping pixels 203 using some (sensor-surface) uniform and/or light field-oblivious approach, such as skipping every second row or column.

[0082] As described above, light field images captured by placing a microlens array 102 above a sensor 103 may consist of a large number of disks 201. Pixels 203 which are nearer to the center of a disk 201 tend to be better illuminated and have a higher signal-to-noise ratio (SNR) than pixels 203 which are nearer to the boundary of a disk 201. In such a light field image, the two directional dimensions of the 4D coordinate space refer to the position of a pixel 203 within a disk 201, and selection of the pixels 203 which are to be skipped as a function of these directional dimensions may be performed to ensure that only pixels 203 closer to the center of a disk 201 are read out from the sensor 103.

[0083] For example, as depicted in Fig. 7, given a configuration of light field sensor 103 and microlens array 102 such that the diameter of each disk image 201 is around 10 sensor pixels 203, an 8x8 center rectangle 731 of pixels 203 may be defined for each disk 201, so that rectangle 731 is close to being fully contained within disk 201. Sensor 103 may incorporate some amount of local memory for buffering rows of pixel data that may be used to pack the 8x8 rectangles 731 into a contiguous block prior to the data being read out of sensor 103.

[0084] In at least one embodiment, in which the sensor pixels 203 are a single color due to being under a color filter array (CFA), center rectangles 731 can be selected to pack together such that after they are packed, the resultant image is a legal example of the CFA pattern across the span of the resultant image. In the case of a (R,GR,GB,B) Bayer sensor, rectangles 731 can be chosen such that (for example) the same color pixel (e.g., R) is at the top-left of each 8x8 block.

[0085] The locations of the pixels 203 to skip and/or the pixel regions to pack together may be specified in any of a number of possible ways. One example is to provide the sensor coordinates of the center of each disk 201. This data may also be stored in the sensor in a small local memory (not shown) dedicated to this purpose.

Per-pixel read-out operations

[0086] In various embodiments, the system and method of the present invention provide sensor read-out patterns that are fully configurable and that may be specified or configured in a per-pixel manner.

[0087] In at least one embodiment, a bitmask may be provided which specifies, for every pixel 203, whether it is skipped or not, and the non-skipped pixels 203 may be packed together in the data that is output from sensor 103. Such a bitmask may be programmed into a local memory in sensor 103, or it may be provided in a DRAM or other memory that sensor 103 may access. Further, multiple bitmasks may be programmed into the sensor to allow rapid switching of read-out patterns.

[0088] In another embodiment, one or more bitmask tiles may be provided, and these tiles may be used repeatedly across different sensor regions to specify which pixels 203 are skipped.

[0089] In a further embodiment, rather than a bitmask specifying pixels 203 which are either read or skipped, a weight image, or one or more weight image tiles, may be provided. As with the bitmask approach described above, the read-out pattern may be specified on a per-pixel basis. However, in such an approach, rather than each pixel's corresponding bitmask Boolean entry specifying whether the pixel 203 is skipped, a per-pixel weighting factor (i.e., a multiplicative factor) may be specified, where such weights are multiplied with the pixel values that are read out. Moreover, any other skipping, binning, resampling, or aggregation of pixels 203 during read-out may be performed in conjunction with such a per-pixel weighting operation.

[0090] In another embodiment, in addition to or instead of per-pixel weighting data being provided, a per-pixel offset value may be provided, wherein the read-out pixel values are computed according to the following formula, where the computed pixel value is clamped to a legal pixel value range, as follows:

[0091] *PixelValue' = CLAMP(PerPixelOffset + PerPixelWeight * PixelValue, 0, MAX)*

[0092] One (of many) possible read-out patterns enabled by per-pixel specification of skipping is a random or pseudo-random pattern; for example, a repeating tiled pattern in which pixels 203 that are skipped have a set of locations that appears to be random.

[0093] In at least one embodiment, the arithmetic operations described herein may be implemented using standard fixed-point arithmetic.

Read-out bit depth modifications

[0094] In at least one embodiment, the read-out bit depths of digital image sensor 103 can be modified to take advantage of the large amount of pixel aggregation performed within light field processing algorithms. By utilizing an appropriate number of bits to encode each raw pixel 203 and defining the mapping function from raw linear values to encoded values, the read-out data rate from the sensor (measured in bytes/second) to attain a given number of pixels/second can be reduced. Any suitable encoding can be used to make use of the light field coordinates of pixels 203 and/or the light field disk pattern on sensor 103.

[0095] One exemplary encoding outputs raw data with a variable number of bits per pixel, where pixels 203 with "better" or "more" light capture during a sensor exposure may have their corresponding values encoded with a higher bit depth. For a light field image captured on sensor 103 beneath a microlens array 102 (according to the architecture described above, for example), the resultant disk image will have pixels 203 with more light captured closer to the centers of disks 201; therefore, more bits may be used to encode disk-center pixels vs. disk-edge pixels.

[0096] Another exemplary encoding may employ a pixel-specific maximum value to which pixel values are clamped. For example, in many cases, pixels near the centers of disks 201 in a light field image are much brighter than pixels near the edges of disks 201, except in the case of over-saturation. Disk-edge pixels may be clamped to a maximum value that is smaller than the values which disk-center pixels may hold.

[0097] A further embodiment may employ a combination of the variable bit depth and variable pixel maximum methods. An example of such a read-out pattern may employ 12 bits per pixel (bpp) to encode values in the range [0,4095] for disk-center pixels 203, and 6 bpp to encode values in the range [0,1023] for disk-edge pixels 203 (where the 64 possible encoded values are evenly spaced out within the range of 1024 pixel values).

[0098] In another exemplary embodiment, one or more lookup tables can be used to map sensor values to encoded values, wherein the lookup tables may be programmed by the user, and the choice of which lookup table to apply to any given pixel 203 is determined according to its light field coordinates, for example according to its position relative to the center of its disk 201. Different lookup tables, and even different entries within a lookup table, may or may not be of varying bit lengths, and the sequence of pixels 203 that is read out of the sensor may have any variable-sized pixel values packed together.

[0099] As with the pre-filtering embodiment, in at least one embodiment, such pixel bit depth modifications may be implemented by logic that operates on a small number of buffered rows of pixels 203 prior to being read out over the sensor interface.

Progressive multi-pass read-out

[0100] In at least one embodiment, the sensor image data can be read out in multiple passes, wherein each pass reads a set of rows that are spaced out across sensor 103 and are interleaved with the rows read out by other passes. Such a read-out method enables features such as the disentanglement of camera motion from object motion, and HDR imaging, by subsequent processing of the data.

[0101] The number of passes, and the corresponding set of rows read by each pass, may be hard-wired, or they may be programmable.

Performing light field-aware processing during read-out

[0102] In at least one embodiment, light field-aware processing can be performed on image sensor 103 such that the data that is read out from sensor 103 has been processed in some way. Examples of light field-aware processing operations include (but are not limited to):

- Transposing light field image data from an "array of disks" format into an "array of sub aperture images" format;
- Converting the 4D data to a 2D image, for example by refocusing it, by producing an all-in-focus or extended depth of field (EDOF) image, or by producing an image with a parallax or perspective shift.

Different read-out patterns across different frames

[0103] In at least one embodiment, different read-out patterns can be provided for different frames, in particular for video. In general, any of the read-out mode embodiments described herein may be varied across different frames.

Light field image read-out on a CCD sensor

[0104] In at least one embodiment, at least some of the image read-out modes described herein can be implemented using a charge-coupled device (CCD) image sensor 103 if some or all of microlens array geometry is known or determined when image sensor 103 is fabricated. Unlike CMOS image sensors, CCDs generally do not have individually addressable pixels 203, and rely on the charge transfer for read-out. This presents a challenge for implementing arbitrary read-out modes on such an image sensor 103, because the local order and pattern of pixel read-out is fixed in the design of the semiconductor device itself.

[0105] One method for implementing full-resolution or reduced-resolution read-out modes that read out the pixels 203 in a specific order or fashion that is dependent on a particular microlens array geometry, or is otherwise well suited for microlens imaging, is to use an interline, frame-interline transfer or any other type of CCD image sensor 103 with interlaced scan. The image sensor 103 is constructed with per-pixel microlenses, photodiodes, transfer gates, vertical charged coupled devices (VCCDs), and/or other customary image sensor parts arranged in accordance with the geometry of the light field microlens array 102, so as to allow the implementation of a read-out mode (or modes) described herein. In other respects, image sensor 103 may be constructed in any fashion suitable for a CCD image sensor.

[0106] Referring now to Fig. 8, there is shown an example arrangement of photodiodes 701 for a read-out mode that skips pixels 203 that are near or on the edge between light field disk images, according to one embodiment. Fig. 8 depicts a logical arrangement of photodiodes 701 and VCCDs 702 for an 8-field interlaced read-out imaging sensor with a hexagonal light field microlens array pattern 703. The transfer gates (or any other part of the metal layer), apertures, color filter array and per-pixel microlenses are omitted for clarity. The diagram is not to scale. In this example, reading out fields 1, 2, 3 and 4 gives a half-resolution mode that only covers pixels 203 in the center of the microlens array image.

Varying the Color Filter Array Pattern of the Image Sensor

[0107] In at least one embodiment, given a microlens array over an image sensor, for example, microlens array 102 over sensor 103, the color filter array (CFA) pattern that is applied to image sensor 103 can be modified to improve the quality of color information captured from the light field. The color chosen for each pixel 203 may (or may not) be a function of its light field coordinates.

[0108] Referring now to Fig. 9, there is shown another example architecture of a light field capture device 109 according to one embodiment. As depicted in Fig. 9, light field sensors 103 include disk pattern 901 (e.g., specifying an arrangement of disks 102 in the captured light field image data formed on sensors 103), color filter array (CFA) grid layout 902, and CFA modifier 903. According to the techniques of the present invention, CFA modifier 903 can modify CFA grid layout 902 based on disk pattern 901.

[0109] Referring now to Fig. 10, there is shown a flow diagram depicting a method for modifying a color filter array (CFA) to improve the quality of color information captured from the light field, according to one embodiment. For illustrative purposes, the method of Fig. 10 will be described with respect to the components and data in Fig. 9.

[0110] In at least one embodiment, CFA modifier 903 accesses 1001 the configuration of disk pattern 901. CFA modifier 903 then determines 1002 how to modify the color filter array (CFA) to improve the quality of the color information captured from the output of microlens array 102. CFA modifier 903 then modifies 1003 CFA grid layout 902 according to its determination. Then, light field sensors 103 capture 1004 light field image data from the output of microlens array 102 in accordance with disk pattern 901 and modified CFA grid layout 102. Light field sensors 103 then send 1005 the captured light field image data to processing circuitry 104.

[0111] In various embodiments, a color filter array can be modified in a variety of ways, including but not limited to: not applying a color filter to some pixels 203, varying color filter pass bands, and/or randomizing the color filter array pattern.

[0112] In various embodiments, CFA pattern modifications include, but are not limited to, the following:

Not applying a color filter to some pixels

[0113] Pixels 203 that receive light that is strongly modulated by the microlens array 102 may have no color filter to increase the amount of photons captured by the pixels 203 during the same exposure duration. In later processing stages, the non-color-filtered pixels 203 can be used as a source of luminance signal (monochrome image) and their chrominance component can be interpolated from nearby pixels 203.

Varying color filter pass bands

[0114] Pixels 203 that receive less light can have a color filter with a wider pass band (subtractive), while pixels 203 that receive more light can have a narrower pass band. For example, pixels 203 towards the edge of the microlens image can have cyan/magenta/yellow color filter pattern while pixels 203 towards the center of the microlens image can have red/green/blue color filter pattern. This allows the edge pixels 203 to attenuate less signal in their color filter, increasing the number of photons reaching the photosensor.

Randomizing the color filter array pattern

[0115] To reduce problems that may occur due to the regularity of color filter array patterns, the color filter array arrangement can be randomized. The type of color filter over each pixel 203 can be recorded and made known to the processing software/hardware.

Varying Pixel Properties of an Image Sensor

[0116] Given a microlens array 102 positioned over an image sensor 103, different amounts of light may be captured by different pixels 203 based on their position under each microlens 201 due to various factors dependent on the sensor angular response, as well as optical characteristics of the microlens array 102 and/or main lens 113. In at least one embodiment, individual pixel properties can be adjusted based on the light field coordinates of each pixel 203 to compensate for these effects and to produce more uniform (or intentionally non-uniform) sampling.

[0117] Referring now to Fig. 11, there is shown another example architecture of a light field capture device 109 according to one embodiment. As depicted in Fig. 11, light field sensors 103 include pixel modifier 1106. In general, pixel modifier 1106 can access the light field coordinates for a pixel 203 and make corresponding modifications to the pixel's 203 properties based on the pixel's 203 light field coordinates.

[0118] Referring now to Fig. 12, there is shown is a flow diagram depicting a method for modifying pixel properties, according to one embodiment.. The method of Fig. 12 will be described with respect to the components and data in Fig. 11.

[0119] Sensor 103 captures 1201 light field image data from the output of microlens array 102, the light field image data including properties for each pixel 203. Then, for each of one or more pixel values included in the light field image data, pixel modifier 1106 accesses coordinates 1130 for the pixel 203, and modifies

1202 the pixel 203 by adjusting one or more properties of the pixel 203 to compensate for non-uniform sampling due to other characteristics of light field capture device 109. For example, pixel modifier 1106 can modify pixel 203 by adjusting properties 1104 based on coordinates 1103. The captured light field image data, including the modified one or more pixels 203, is then sent 1203 to processing circuitry 104.

[0120] Examples of pixel properties that can be adjusted include, but are not limited to:

- Exposure duration that is unique to each pixel 203.
- Any sort of gain applied to the signal at the pixel amplifier, column amplifier, row amplifier and/or any other analog or digital amplification stage.
- Any sort of bias and/or offset applied to the signal at the photodiode, any amplifier, digital/analog converter (DAC) and/or any other processing stage.

[0121] These properties may be varied per-pixel, and/or they may be varied per group of pixels 203. For example, in at least one embodiment, there can be a fixed number of different sets of parameters, and each pixel 203 can be configured according to one of these parameter sets.

[0122] Methods for adjusting these properties include, but are not limited to:

- Any sort of post-fabrication local trimming of the semiconductor.
- Implementing (for example, in hardware) settable per-pixel or per-pixel-group exposure scale or offset, signal gain, signal bias or signal offset that is provided as a digital or analog signal prior to image exposure.
- Implementing (for example, in hardware) settable per-pixel or per-pixel-group exposure scale or offset, signal gain, signal bias or signal offset that is stored in semiconductor fuses during manufacture time.

- Implementing (for example, in hardware) per-pixel or per-pixel-group signal gain, signal bias or signal offset that is provided synchronously during image read-out as a digital or analog signal.

Moving/Jittering Pixels and/or Microlenses

[0123] As described above, in at least one embodiment, pixels 203 on sensor 103 may be arranged in a regular pattern, such as a square pattern. Likewise, lenses 201 on microlens array 102 may also be arranged in a regular pattern, such as a square pattern or a hexagonal pattern. There may be advantages, however, to perturbing either or both of these regular patterns such that small, random variations in position are introduced. Such random variations in position are referred to herein as "jitter"; the introduction of jitter is referred to herein as "jittering". It is well known in the field of computer graphics that jittering sample locations converts aliasing to noise. See, for example, Cook, Robert L., *Stochastic Sampling in Computer Graphics*, ACM Trans. Graph. 5, 1 (1986). Because the positions of microlenses 201 and pixels 203 essentially determine the sample pattern of the light field entering camera 100, these advantages may also accrue to light field sampling. A related advantage is that the regularity of sample patterns in re-projections of the light field may also be reduced. There may be additional advantages as well.

[0124] Referring now to Fig. 13, there is shown another example architecture of a light field capture device 109 according to one embodiment. As depicted in Fig. 13, light field capture device 109 includes jitter module 1301. Jitter module 1301 is configured to introduce jitter into microlens array 102 and/or light field sensor(s) 103.

[0125] Referring now to Fig. 14, there is shown a flow diagram depicting a method for introducing jitter into optical system components, according to one embodiment. The method of Fig. 14 will be described with respect to the components and data in Fig. 13.

[0126] In at least one embodiment, light that 1303 has passed through aperture 112 and main lens 113 is accessed. As depicted in Fig. 13, light 1302 passes into camera 100 and light 1303 passes out of optics 101. Jitter module 1301 introduces 1402 random variations, for example by changing positions of lenses 201 in microlens array 102 and/or pixels 203 in one or more light field sensors 103.

[0127] Subsequent to introduction of the random variations, light field image data 1304 is captured 1403 from the accessed light 1303, for example by microlens array 102 and light field sensor(s) 103. The captured light field image data 1304 is sent 1404 to processing circuitry 104.

[0128] Jitter patterns may be random at any scale. At one extreme, the pattern may extend throughout the range, i.e., across the entire microlens array 102 or the entire sensor 103. At the other extreme, the pattern may be a small tile that is repeated across microlens array 102 or sensor 103. Between these extremes lie larger tiles, and random patterns of larger tiles. The motivation for tiling may be reduced processing cost, because the tables required to correctly interpret sample locations are smaller. Much of the advantage of jittered sampling may accrue with fairly small tiles. For example, the same pattern of pixel jitter might be implemented for the tens of pixels 203 in each disk.

[0129] In at least one embodiment, pixels 203 on sensor 103 can have their true locations jittered. Alternatively, pixels 203 can be placed on a regular grid, but made to appear jittered by making adjustments to lenses that are placed on each pixel location. (These lenses are intended to guide light impinging on sensor 103 toward the light-sensitive part of the electronic pixel structure.) Adjusting only the optics on the surface of sensor 103, rather than making changes to sensor 103 itself, can be less expensive, and can be implemented with a larger tiling. Pixel jitter can be performed in conjunction with variation in pixel size, which can also be introduced either directly in sensor 103, or by making changes to the optics on the surface of sensor 103.

[0130] In at least one embodiment, jittering the microlens positions and/or the pixel locations is performed in such a manner as to ensure that no two lenses are positioned closer than the diameter of the disks. Thus, disk overlap is avoided, which otherwise can cause pixel values to not be correctly interpreted. The closeness constraint may be satisfied with random jittering. Alternatively it may be more efficient to satisfy the closeness constraint as additional constraint on the positions of the microlenses. For example, an annealing algorithm may allow both near-random jitter and a minimal-distance constraint to be implemented simultaneously. In particular, jitter can be randomly introduced throughout the tile, and then in cases where the minimum-distance constraint is violated, samples can be re-jittered; this process can be repeated until constraints are satisfied.

Designing For Integer-Pitch Disk Images

[0131] In at least one embodiment, modifications can be made to microlens array 102 and main lens 113 design and placement within the optical system 101, so as to produce disk images with vertical and/or horizontal pitches of integer numbers of sensor pixels 203, where the integer pitch is chosen to enable processing approaches that are cheaper, faster, and/or higher quality. Such approaches include (but are not limited to) those described below.

[0132] The pitch of the disk image on sensor 103 is governed by the pitch of microlens array 102, its separation from sensor 103, and the distance to main lens 113 exit pupil. Choosing these parameters appropriately, and also ensuring that microlens array 102 is not spatially rotated with respect to sensor 103, allows light field disk images to be captured in which the disk pitch in either or both of the horizontal and vertical directions is an integer.

[0133] In addition to the disk pitch being an integer value, another design constraint that can be applied is to ensure that microlens array 102 is properly aligned on top of sensor 103 such that each row of microlenses 201 in microlens array 102 is parallel to the rows of sensor pixels 203. This is possible using wafer-to-wafer manufacturing techniques, in addition to lithographic manufacturing approaches.

[0134] For example, referring again to Figs. 1A, 1B, 2, and 7, main lens 113 and microlens array 102 can be arranged to produce disk images 201 (or center rectangles 601) with vertical and/or horizontal pitches of integer numbers of sensor pixels 203 on sensor(s) 103. Alternatively or in combination, the separation between microlens array 102 and sensor(s) 103 can be selected to facilitate vertical and/or horizontal pitches of integer numbers of sensor pixels 203 on sensor(s) 103. Alternatively or in combination, microlens array 102 can be configured to ensure that it is not spatially rotated with respect to sensor(s) 103. Alternatively or in combination, microlens array 102 can be configured to ensure that it is properly aligned on sensor(s) 103 such that each row of microlenses 201 in microlens array 102 is parallel to a row of sensor pixels 203 in sensor 103.

[0135] In at least one embodiment, main lens 113 is a moving main lens. Main lens 113 can be of a design that ensures the disk image pitch on sensor(s) 103 remains constant and an integer as main lens 113 moves (e.g., as it zooms). For example, main lens 113 may have an exit pupil sufficiently far away from the sensor surface of light field sensor(s) 103 (relative to the sensor dimensions) for all focal lengths.

Transposition to an array of sub-aperture images

[0136] In at least one embodiment, the optical system is configured so that the captured light field disk images 201 have integer-pitch disks on a square lattice, with each disk image 201 being contained within a square NxN region of source pixels 203. Further, the light field image data is transposed from its "array of disks" representation into its equivalent "array of sub-aperture images" representation, as described in Ng et al. Such transposition may occur in any of the following places, or at any other suitable location:

- On sensor 103 itself, so that the raw light field image data that is read out from sensor 103 is already in its transposed layout.
- On a processing element connected to sensor 103, such as a camera system-on-chip (SoC), within the camera processing flow.
- On light field image data that has been saved into a file.

[0137] The transposition of the data may be done in either the raw domain (i.e., prior to demosaicing the data), or on the light field image data after it has been converted to full color (e.g., in the RGB or YUV domains).

[0138] Light field image data that is represented in this layout may have much less high-frequency modulation. The benefits of arranging the light field image data in this layout may include, for example:

- Increased ability to process the light field image data as if it were a 2D image, for example demosaicing it (in the case of raw light field image data), JPEG-encoding it, video-encoding a sequence of such frames, and the like. This is due to the fact that the light field image data, encoded in this format, appears to be just an atlas of 2D images. When represented as an "array of disks", the light field image data contains a high-frequency modulation pattern due to the disk pattern that often results in the data being degraded if a standard 2D image algorithm is applied to the data.
- Ability to perform light field processing of the data more cheaply, efficiently, or quickly.

[0139] In the case of performing such a transposition on raw light field image data that was captured using a sensor with a Color Filter Array (CFA) (e.g., a Bayer sensor), the light field image data post-transposition may no longer contain a uniform color pattern across the extent of the data. For example, as depicted in Fig. 15, given light field image 200 which has 2x2 disks 201, with each disk 201 being 3x3 pixels (N=3), this could be transposed into sub-aperture image grid 1503A with 3x3 sub-aperture images, each image having 2x2 pixels 203.

[0140] In another embodiment, as depicted in Fig. 16, the CFA pattern can be modified on the sensor such that the light field image data, post-transposition, is a legitimate example of a raw CFA pattern, such as a Bayer mosaic pattern. One way to implement this on light field image 200 is to use a CFA that causes each disk image 201 to be a uniform color, with the color pattern of disks in the disk image being a legal mosaic pattern. This can be transposed into sub-aperture image grid 1503B with 3x3 sub-aperture images, each of 2x2 pixels.

Raw transposition for high-resolution refocusing to a specific depth

[0141] In at least one embodiment, an optical system is implemented that results in captured light field images with an integer disk pitch that allows for a fast reordering of the captured light field image data in the raw Bayer domain such that the resultant reordered light field image data may be directly interpreted as a 2D image that is focused at a specific depth and processed using standard 2D image processing algorithms (including demosaicing) to yield a final image that can be displayed or output.

[0142] In at least one embodiment, the optical system may be characterized as follows.

- Microlens array (MLA) 102 with square packing, integer N, and proper alignment.
- Optical system for video and/or live view set up in order to enable viewing of a particular focal plane (in a fixed focus camera, this focal plane may be near the infinity focal plane) as follows:
    - Consider the set of all sub-aperture images, corresponding to a set of positions within the virtual aperture of main lens 113, where the sub-aperture images are viewed at "MLA resolution" in that the number of pixels 203 across a row in a sub-aperture image is approximately the same as the number of microlenses 201 across a row of the microlens array 102.
    - Define L such that scene objects which are in focus in the particular focal plane will be in focus in an output image which is formed by the "shift-and-add" method of refocusing described in Ng et al. when the extreme sub-aperture images corresponding to the points around the perimeter of the virtual aperture are each shifted by L/2 pixels. The direction of the shift is determined by whether

the particular focal plane under consideration is "in front of" or "behind" the optically captured focal plane (see Ng et al.).

- In operation, camera 100 refocuses to the focal plane characterized as above by the parameter L according to the method described below.
  - N and L are selected such that N/L is integral. Let P = N/L.
  - The sensor has a read-out mode that can read a single block of PxP pixels, repeating every NxN pixels.
  - Microlens array 102 is aligned with sensor 103 such that each PxP read-out block is near the center of the disk 201 of the pixel 203 corresponding to the microlens array 102.

[0143] Referring now to Figs. 17A through 17D, there is shown an example sensor 103 having a read-out mode that can read a single block of PxP pixels 203, repeating every NxN pixels 203. Fig. 17A depicts an optical system 101A with focal plane 1711, microlens array 102, and sensor 103. In Fig. 17A, the distance between focal plane 1711 and microlens array 102 is four times the distance between microlens array 102 and sensor 103 (i.e., L=4). Fig. 17B depicts light field image 200A having 2x2 disks 201, with each disk 201 being 8x8 pixels (N=8). Light field image 200A can be generated by the components of optical system 101A. Fig. 17C depicts subsampling pattern 1704A of light field image 200A. Fig. 17D depicts a subsampled portion 1706A of light field image 200A taken using subsampling pattern 1704A and corresponding transposition 1707A for L = N/2. Within transposition 1707A projection, Bayer mosaic pixels 203 are adjacent to both X/Y and U/V neighbors for demosaicing.

[0144] Referring now to Figs. 18A through 18D, there is shown another example sensor 103 having a read-out mode that can read a single block of PxP pixels 203, repeating every NxN pixels 203. Fig. 18A depicts an optical system 101B with focal plane 1711, microlens array 102, and sensor 103. In Fig. 18A, the distance between focal plane 1711 and microlens array 102 is three times the distance between microlens array 102 and sensor 103 (i.e., L=3). Fig. 18B depicts light field image 200B having 2x2 disks 201, with each disk 201 being 9x9 pixels (N=9). Light field image 200B can be generated by the components of optical system 101B. Fig. 18C depicts subsampling pattern 1704B of light field image 200B. Fig. 18D depicts a subsampled portion 1706B of light field image 200B taken using subsampling pattern 1704B and corresponding transposition 1707B for L = N/3. Within transposition 1707B projection, Bayer mosaic pixels 203 are adjacent to both X/Y and U/V neighbors for demosaicing.

[0145] In operation, camera 100 subsamples the image from the PxP blocks and assembles the resulting image. In the case that L is positive (in the background), the pixels 203 within each PxP block are flipped across the center point (Figure 18D). In the case that L is negative, the pixels 203 remain in place.

[0146] In at least one embodiment, the resulting image has the following properties:

- It is focused at the focal plane characterized by the parameter L.
- The resulting image is SensorWidth * P / N pixels wide and SensorHeight * P / N pixels high. In the case of a 4000x3000 sensor (12MP), N = 10 and L = 5, the output image is 800x600 pixels.
- Each pixel 203 in the resulting Bayer image is adjacent to both its neighbors in X/Y and U/V.
- The depth of field is P times the optical system, in effect creating an image with a somewhat extended depth of field.

[0147] One advantage of this approach is that it can create extended depth-of-field (EDOF) video and live-view in a highly efficient manner. The projection in the Bayer mosaic allows for a demosaicing with true neighbors in the X,Y,U,V space. The method also results in relatively high resolution output.

Integer-pitch hexagonal microlens array layouts

[0148] In at least one embodiment, a light field optical system includes a microlens array 102 on which microlenses 201 are laid out in a non-rectangular lattice, such as, for example, a hexagonal lattice, where the lattice may be stretched in one dimension (e.g., vertically or horizontally) to achieve an integer pitch in each dimension. For example, with a microlens array 102 with a hexagonal layout, the microlens pitch may be chosen to result in a horizontal disk pitch on the sensor of N=10 pixels, but in this case, the vertical disk pitch will be N*SQRT(3)/2 = 8.66 pixels. Stretching the microlens array layout vertically by 4% would result in a vertical pitch of 9.

Positioning and/or Orienting Microlens Array 102 on top of Sensor 103 based on Available Read-out Modes of Sensor 103

[0149] In at least one embodiment, the position and orientation of microlens array 102 above sensor 103 can be determined based on the read-out modes of sensor 103. Given a microlens array 102 and an image sensor 103, an optimal orientation and position of microlens array 102 over image sensor 103 can be determined. In at least one embodiment, this orientation and position are then applied to microlens array 102 during the manufacturing process before microlens array 102 is fixed in place.

[0150] Referring now to Fig. 19, there is shown a flow diagram depicting a method for determining and configuring a microlens array 102 for use in a light field image capture device 109, according to one embodiment. This method will be described with respect to the components of Figures 1A, 1B, and 5.

[0151] First, characteristics of microlens array 102 are accessed 1901. Then, characteristics of sensor(s) 103, including the read-out modes of sensor(s) 103, are accessed 1902. An optimal configuration for microlens array 102 is determined 1903 based on the characteristics of microlens array 102 and the characteristics of sensor(s) 103, including the read-out modes of image sensor(s) 103. The optimal configuration for is stored 1904 in a storage device, for application to microlens array 102 during manufacture of light field capture device 109. The optimal configuration can be stored, for example, in manufacturing equipment used to manufacture camera 100.

[0152] In at least one embodiment, the system considers a set of (potentially all) physical rotations of microlens array 102 about the axis orthogonal to the image sensor plane (Z-axis) and all physical translations of microlens array 102 in the plane parallel to the image sensor plane (XY-axis). Also, the system considers the set of all read-out modes of sensor 103 (including, for example, binning, skipping, resampling, scaling, and/or some combination thereof.). For each sensor read-out mode, two different orientation/positions of the microlens array 102 can be compared by computing and considering the following factors:

- The ratio of the average modulation of the read-out pixels 203 to the average modulation of all pixels 203. For example, suppose the read-out mode skips pixels 203 according to a periodic pattern of size N both vertically and horizontally. A translation of microlens array 102 that maximizes the number of read-out pixels 203 that are in areas with minimal modulation would be preferable to one that does not.
- Which section of the light field is captured by the read-out mode if it is a reduced resolution read-out mode. The set of samples in each read-out frame can be interpreted with respect to their light field coordinates. The shape of this sample distribution for a given mode will change with translation and rotation of microlens array 102, and some distributions will be better than others. For example, suppose the read-out mode skips pixels 203 according to a periodic pattern of size N both vertically and horizontally, and each light field disk image happens to contained within an NxN pixel square on sensor 103. A translation and rotation of microlens array 102 that makes sure the center pixel 203 is read out under each microlens 102 would produce the center sub-aperture image. See, for example, Ng et al.
- Which parts of the light field are mixed together during any scaling, binning, and/or resampling applied by image sensor 103 in the given read-out mode. Each output pixel in a scaled, binned, or sub-sampled version of a light field image may be computed as a combination of sensor pixels 203 (which may be a weighted average). One criterion which may be applied to evaluate a particular microlens array

placement is the spread of directional information in the light field coordinates of the set of sensor pixels 203 which were used to compute the output pixel. Choosing a placement which results in a larger average spread of directional coordinates in each output pixel may result in fewer aliasing artifacts in the output image.

MLA Designs to Deal with Large Chief-Ray Angle (CRA)

[0153] The performance of a sensor 103 intended for use with a telecentric lens for as a main lens 113 can be (potentially dramatically) improved by tilting microlenses 201 towards the optical axis of main lens 113, so that microlenses 201 receive rays of light perpendicular (or more nearly perpendicular) to their own local surfaces. For example, referring to Figure 1B, the lenses in microlens array 102 can be tilted towards the optical access of main lens 113.

[0154] Referring now to Fig. 20, there is shown a top-down view of two example microlens arrays 102. Top-down view 2001 depicts a flat microlens array 102A. Top-down view 2002 depicts a tilted microlens array 102B. In top-down view 2002, each microlens 201 is tilted towards optical axis (x, y = 0, 0). Referring now also to Fig. 21, there are shown example 3D plots of the top-down views depicted in Fig. 20. 3D plot 2101A corresponds to flat microlens array 102A. 3D plot 2101B corresponds to tilted microlens array 102B. In the color versions of Figs. 20 and 21, red indicates high elevations, while blue indicates low elevations.

[0155] Referring now to Fig. 22, there is shown an example 2D slice 2201 through a microlens array 102 containing tilted microlenses 201. 2D slice 2201 illustrates how each tilted microlens 201 is joined to its neighbors with planes. If the incident medium of the ray is air, the planes are oriented such that they are parallel to rays coming from the center of main lens's 113 exit pupil. If the incident medium of the ray is not air, and therefore has a refractive index greater than one, the planes are oriented such that they are parallel to the refracted angle of the rays coming from the center of the main lens. This is done to minimize the effect of these scattering surfaces, as seen by an observer at the center of the main lens's 113 exit pupil. Further optimization of the tilted MLA side wall angle can be performed, so as to account for the f-number and vignetting of the main lens and scattering, reflection, and total internal reflection from the lens surfaces.

[0156] Referring now to Figs. 23A and 23B, there are shown two examples of different types of optimization of the tilted MLA side wall angle. In Fig. 23A, MLA 102 is shaped from the bottom edge of incident medium 2301 (which may be, for example, glass, polymer, or other light-transmissive material), with an air gap 2304 between medium 2301 and sensor 103. Light rays 202 arriving from main lens 113 exit pupil refract when they hit medium 2301. Planes 2302 of MLA 102 are shaped and oriented so that they match the refracted angle of the incident light, and so that they properly focus light rays 202 onto sensor 103.

[0157] In Fig. 23B, MLA 102 is shaped from the top edge of incident medium 2301, with no air gap between medium 2301 and sensor 103. Here, light rays 202 arriving from main lens 113 exit pupil refract when they hit planes 2302 of MLA 102, which are shaped from the top edge of incident medium 2301. Accordingly, in this embodiment, planes 2302 are shaped and oriented so that they match the angle of the incident light in air, and so that they properly focus light rays 202 onto sensor 103.

[0158] The present invention has been described in particular detail with respect to possible embodiments. Those of skill in the art will appreciate that the invention may be practiced in other embodiments. First, the particular naming of the components, capitalization of terms, the attributes, data structures, or any other programming or structural aspect is not mandatory or significant, and the mechanisms that implement the invention or its features may have different names, formats, or protocols. Further, the system may be implemented via a combination of hardware and software, as described, or entirely in hardware elements, or entirely in software elements. Also, the particular division of functionality between the various system components described herein is merely exemplary, and not mandatory; functions performed by a single system component may instead be performed by multiple components, and functions performed by multiple components may instead be performed by a single component.

[0159] In various embodiments, the present invention can be implemented as a system or a method for performing the above-described techniques, either singly or in any combination. In another embodiment, the present invention can be implemented as a computer program product comprising a nontransitory computer-readable storage medium and computer program code, encoded on the medium, for causing a processor in a computing device or other electronic device to perform the above-described techniques.

[0160] Reference in the specification to "one embodiment" or to "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least one embodiment of the invention. The appearances of the phrase "in at least one embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

[0161] Some portions of the above are presented in terms of algorithms and symbolic representations of operations on data bits within a memory of a computing device. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps (instructions) leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical, magnetic or optical signals capable of being stored, transferred, combined, compared and otherwise manipulated. It is convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like. Furthermore, it is also convenient at times, to refer to certain arrangements of steps requiring physical manipulations of physical quantities as modules or code devices, without loss of generality.

[0162] It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "displaying" or "determining" or the like, refer to the action and processes of a computer system, or similar electronic computing module and/or device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system memories or registers or other such information storage, transmission or display devices.

[0163] Certain aspects of the present invention include process steps and instructions described herein in the form of an algorithm. It should be noted that the process steps and instructions of the present invention can be embodied in software, firmware and/or hardware, and when embodied in software, can be downloaded to reside on and be operated from different platforms used by a variety of operating systems.

[0164] The present invention also relates to an apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a general-purpose computing device selectively activated or reconfigured by a computer program stored in the computing device. Such a computer program may be stored in a computer readable storage medium, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, flash memory, solid state drives, magnetic or optical cards, application specific integrated circuits (ASICs), or any type of media suitable for storing electronic instructions, and each coupled to a computer system bus. Further, the computing devices referred to herein may include a single processor or may be architectures employing multiple processor designs for increased computing capability.

[0165] The algorithms and displays presented herein are not inherently related to any particular computing device, virtualized system, or other apparatus. Various general-purpose systems may also be used with programs in accordance with the teachings herein, or it may prove convenient to construct more specialized apparatus to perform the required method steps. The required structure for a variety of these systems will be apparent from the description provided herein. In addition, the present invention is not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the present invention as described herein, and any references above to specific languages are provided for disclosure of enablement and best mode of the present invention.

[0166] Accordingly, in various embodiments, the present invention can be implemented as software, hardware, and/or other elements for controlling a computer system, computing device, or other electronic device, or any combination or plurality thereof. Such an electronic device can include, for example, a processor, an input device (such as a keyboard, mouse, touchpad, trackpad, joystick, trackball, microphone, and/or any combination thereof), an output device (such as a screen, speaker, and/or the like), memory, long-term storage (such as magnetic storage, optical storage, and/or the like), and/or network connectivity, according to techniques that are well known in the art. Such an electronic device may be portable or nonportable. Examples of electronic devices that may be used for implementing the invention include: a mobile phone, personal digital assistant, smartphone, kiosk, server computer, enterprise computing device, desktop computer, laptop computer, tablet computer, consumer electronic device, television, set-top box, or the like. An electronic device for implementing the present invention may use any operating system such as, for example: Linux; Microsoft Windows, available from Microsoft

Corporation of Redmond, Washington; Mac OS X, available from Apple Inc. of Cupertino, California; iOS, available from Apple Inc. of Cupertino, California; and/or any other operating system that is adapted for use on the device.

[0167] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of the above description, will appreciate that other embodiments may be devised which do not depart from the scope of the present invention as described herein. In addition, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and may not have been selected to delineate or circumscribe the inventive subject matter. Accordingly, the disclosure of the present invention is intended to be illustrative, but not limiting, of the scope of the invention, which is set forth in the claims.

CLAIMS

What is claimed is:

1. In a light field image capture device, the light field image capture device including at least one sensor and processing circuitry, the processing circuitry configured to process captured light field image data to generate visual output, a method for reducing the size of captured light field image data, the method comprising:

capturing light field image data at the at least one sensor, the light field image data representing output of a microlens array;

determining a read-out mode of the at least one sensor;

pre-processing the captured light field image data in accordance with a the determined read-out mode to reduce the data size of the captured light field image data; and

sending the pre-processed captured light field image data to the processing circuitry.

2. The method of claim 1, wherein pre-processing the captured light field image data comprises performing at least one selected from the group consisting of: sub-sampling, binning, and resampling on the captured light field image data.

3. The method of claim 2, wherein pre-processing the captured light field image data comprises filtering the captured light field image data prior to performing at least one selected from the group consisting of: sub-sampling, binning, and resampling the captured light field image data.

4. The method of claim 1, wherein pre-processing the captured light field image data comprises skipping at least one pixel on the at least one sensor, based on light field coordinates of the at least one pixel.

5. The method of claim 1, further comprising, prior to pre-processing the captured light field image data:

buffering at least a portion of the captured light field image data in local memory at the at least one sensor; and

accessing the at least a portion of the captured light field image data from the local memory.

6. The method of claim 1, wherein pre-processing the captured light field image data in accordance with a determined read-out mode comprises processing the captured light field image data in accordance with a read-out mode configured on a per-pixel basis.

7. The method of claim 6, wherein processing the captured light field image data in accordance with a read-out mode configured on a per-pixel basis comprises using at least one of:

a bitmask;

at least one bitmask tile;

at least one weight image tile; and

a per-pixel offset;

to process pixels on a per-pixel basis.

8. The method of claim 1, wherein pre-processing the captured light field image data comprises using at least one of variable bit depths and variable pixel maximum values based on the light field coordinates of at least one pixel on the at least one sensor.

9. The method of claim 1, wherein pre-processing the captured light field image data comprises performing light field aware processing on the light field image data.

10. The method of claim 1, wherein pre-processing the captured light field image data comprises:

processing at least one frame of the captured light field image data in accordance with the determined read-out mode; and

processing at least one other frame of the captured light field image data in accordance with a second different read-out mode.

11. The method of claim 1, wherein pre-processing the captured light field image data comprises reading out the captured light field image data from a buffer in a plurality of different passes.

12. The method of claim 1, wherein the at least one sensor include a charge-coupled device (CCD) image sensor, and wherein pre-processing the captured light field image data accordance with a specified read-out mode comprises implementing the specified read-out mode using the charge-coupled device (CCD) image sensor.

13. The method of claim 12, wherein implementing the specified read-out mode using the charge-coupled device (CCD) image sensor comprises implementing a reduced-resolution read-out mode using a charge-coupled device (CCD) image sensor with interlaced scan.

14. In a light field image capture device, the light field image capture device including a microlens array, at least one sensor, a disk pattern formed on the sensor, a color filter array (CFA) grid layout, and processing circuitry, the processing circuitry configured to process captured light field image data to generate visual output, the disk pattern and the color filter array (CFA) interoperating to convert output from the microlens array into captured light field image data, a method for modifying the color filter array (CFA), the method comprising:

accessing the configuration of the disk pattern;

determining how to modify the color filter array (CFA) to improve the quality of the color information captured from the output of the microlens array;

modifying the color filter array (CFA) in accordance with the determination;

capturing light field image data from the output of the microlens array in accordance with the disk pattern and the modified color filter array (CFA); and

sending the captured light field image data to the processing circuitry.

15. The method of claim 14, wherein modifying the color filter array (CFA) in accordance with the determination comprises modifying the color filter array so that no color filter is applied to at least one pixel.

16. The method of claim 14, wherein modifying the color filter array (CFA) in accordance with the determination comprises modifying color filter pass bands for at least one pixel.

17. The method of claim 14, wherein modifying the color filter array (CFA) in accordance with the determination comprises randomizing a color filter array (CFA) pattern.

18. In a light field image capture device, the light field image capture device including at least one sensor and processing circuitry, the processing circuitry configured to process captured light field image data to generate visual output, a method for modifying pixel properties of the at least one sensor, the method comprising:

capturing light field image data at the at least one sensor, the light field image data representing output of a microlens array, the light field image data including properties for each of a plurality of pixels of the at least one sensor;

for each of at least one pixel in the at least one sensor, and based on light coordinates of the at least one pixel, modifying the pixel by adjusting at least one property of the pixel to compensate for non-uniform sampling due to other characteristics of the light field image capture device; and

sending the captured light field image data, including the modified at least one pixel, to the processing circuitry.

19. The method of claim 18, wherein modifying the pixel by adjusting at least one property of the pixel to compensate for non-uniform sampling due to other characteristics of the light field image capture device comprises adjusting at least one property of the pixel to compensate for factors related to at least one of: image sensor angular response, a microlens array, and a main lens.

20. The method of claim 18, wherein modifying the pixel by adjusting at least one property of the pixel to compensate for non-uniform sampling due to other characteristics of the light field image capture device comprises adjusting at least one of: exposure duration, gain, and bias for the pixel.

21. The method of claim 18, wherein modifying the pixel by adjusting at least one property of the pixel to compensate for non-uniform sampling due to other characteristics of the light field image capture device comprises implementing pixel adjustment using at least one of: post-fabrication location trimming of a semiconductor, a digital or analog signal, and fusing a scale or offset into a semiconductor.

22. In a light field image capture device, the light field image capture device including an aperture, a main lens, a microlens array, at least one sensor, and processing circuitry, the lenses on the microlens array arranged in a regular

pattern, the pixels on the at least one sensor arranged in a regular pattern, the microlens array and at least one sensor interoperating to capture light field image data from light passing through the aperture and the main lens, a method for perturbing at least one regular pattern of the light field image capture device to increase the quality of captured light field image data, the method comprising:

accessing light that has passed through the aperture and the main leans;

introducing random variations into at least one of: the regular pattern of lenses in the microlens array and the regular pattern of pixels in the at least one sensor;

subsequent to introduction of the random variations, capturing light field image data from the accessed light; and

sending the captured light field image data to the processing circuitry.

23. The method of claim 22, wherein introducing random variations into at least one of: the regular pattern of lenses and the regular pattern of pixels comprises introducing a jitter pattern into at least one of: the regular pattern of lenses and the regular pattern of pixels.

24. The method of claim 23, wherein introducing a jitter pattern into at least one of the regular pattern of lenses and the regular pattern of pixels comprises introducing a jitter pattern into the regular pattern of lenses that extends across the entire microlens array.

25. The method of claim 23, wherein introducing a jitter pattern into at least one of the regular pattern of lenses and the regular pattern of pixels comprises introducing a jitter pattern into the regular pattern of pixels that extends across the entirety of at least one sensor.

26. The method of claim 23, wherein introducing a jitter pattern into at least one of the regular pattern of lenses and the regular pattern of pixels comprises introducing a jitter pattern tile into the regular pattern of lenses, the

jitter pattern tile being repeated a plurality of times across the entire microlens array.

27. The method of claim 23, wherein introducing a jitter pattern into at least one of the regular pattern of lenses and the regular pattern of pixels comprises introducing a jitter pattern tile into the regular pattern of pixels, the jitter pattern tile being repeated a plurality of times across the entire at least one sensor.

28. An optical system, comprising:

a main lens;

a microlens array, the microlens array including a plurality of microlenses; and

at least one image sensor, each image sensor having a plurality of pixels;

wherein the main lens, the microlens array, and the at least one image sensor are configured and arranged relative to one another so that at least one of the horizontal pitch and vertical pitch of disk images on the one of more light image sensors equals an integer number of pixels.

29. The optical system of claim 28, wherein the main lens, the microlens array, and the at least one image sensor are configured and arranged relative to one another so that the disk images are a square lattice of NxN pixels.

30. The optical system of claim 29, wherein the main lens, the microlens array, and the one or more light image sensors are configured and arranged relative to one another so as to transpose an array of disks representation of light field image data into an equivalent array of sub-aperture images representation of the light field image data.

31. The optical system of claim 30, wherein the main lens, the microlens array, and the one or more light image sensors are configured and arranged to transpose an array of disks representation of light field image data into an equivalent array of sub-aperture images representation of the light field image data on at least one of: raw domain data and full color data.

32. The optical system of claim 30, wherein the main lens, the microlens array, and the one or more light image sensors are configured and arranged to reorder light field image data into reordered light field image data that is directly interpretable as a 2D image.

33. The optical system of claim 28, wherein the microlens array has a hexagonal layout.

34. A method for determining a configuration for a microlens array that is to be positioned over an image sensor for use in a light field image capture device, the method comprising:

accessing characteristics of the microlens array;

accessing characteristics of the image sensor, including the read-out modes of the image sensor;

determining an optimal configuration for the microlens array based on the characteristics of the microlens array and the characteristics of the image sensor, including the read-out modes of the image sensor; and

storing the optimal configuration for application to the microlens array during manufacture of the light field capture device.

35. The method of claim 34, wherein determining an optimal configuration for the microlens array comprises determining an optimal position for the microlens array over the image sensor.

36. The method of claim 34, wherein determining an optimal configuration for the microlens array comprises determining an optimal orientation for the microlens array over the image sensor.

37. The method of claim 34, wherein determining an optimal configuration for the microlens array comprises considering at least one physical rotation of the microlens array about an axis orthogonal to the image sensor.

38. The method of claim 34, wherein determining an optimal configuration for the microlens array comprises considering at least one physical translation of the microlens array in a plane parallel to the image sensor plane.

39. The method of claim 34, wherein determining an optimal configuration for the microlens array comprises considering at least one read-out mode of the sensor

40. The method of claim 39, wherein each read-out modes is selected from the group consisting of: binning, skipping, resampling, and scaling.

41. A computer program product for use in a light field image capture device, the light field image capture device including at least one sensor and processing circuitry, the processing circuitry configured to process captured light field image data to generate visual output, the computer program product for implementing a method for reducing the size of captured light field image data, the computer program product comprising at least one computer storage device having stored thereon computer-executable instructions that, when executed at a processor, cause the light field image capture device to:

capture light field image data at the at least one sensor, the light field image data representing output of a microlens array;

determine a read-out mode of the at least one sensor;

pre-process the captured light field image data in accordance with a the determined read-out mode to reduce the data size of the captured light field image data; and

send the pre-processed captured light field image data to the processing circuitry.

42. The computer program product of claim 41, wherein the computer program product is configured to cause the light field image capture device to pre-process the captured light field image data by:

processing at least one frame of the captured light field image data in accordance with the determined read-out mode; and

processing at least one other frame of the captured light field image data in accordance with a second different read-out mode.

43. A computer program product for use in a light field image capture device, the light field image capture device including a microlens array, at least one sensor, a disk pattern formed on the sensor, a color filter array (CFA) grid layout, and processing circuitry, the processing circuitry configured to process captured light field image data to generate visual output, the disk pattern and the color filter array (CFA) interoperating to convert output from the microlens array into captured light field image data, the computer program product comprising at least one computer storage device having stored thereon computer-executable instructions that, when executed at a processor, cause the light field image capture device to:

access the configuration of the disk pattern;

determine how to modify the color filter array (CFA) to improve the quality of the color information captured from the output of the microlens array;

modify the color filter array (CFA) in accordance with the determination;

capture light field image data from the output of the microlens array in accordance with the disk pattern and the modified color filter array (CFA); and

send the captured light field image data to the processing circuitry.

44. A computer program product for use in a light field image capture device, the light field image capture device including at least one sensor and processing circuitry, the processing circuitry configured to process captured light field image data to generate visual output, the computer program product comprising at least one computer storage device having stored thereon computer-executable instructions that, when executed at a processor, cause the light field image capture device to:

capture light field image data at the at least one sensor, the light field image data representing output of a microlens array, the light field image data including properties for each of a plurality of pixels of the at least one sensor;

for each of at least one pixel in the at least one sensor, and based on light coordinates of the at least one pixel, modify the pixel by adjusting at least one property of the pixel to compensate for non-uniform sampling due to other characteristics of the light field image capture device; and

send the captured light field image data, including the modified at least one pixel, to the processing circuitry.

45. The computer program product of claim 44, wherein the computer program product is configured to cause the light field image capture device to modify the pixel by adjusting at least one property of the pixel to compensate for factors related to at least one of: image sensor angular response, a microlens array, and a main lens.

46. The computer program product of claim 44, wherein the computer program product is configured to cause the light field image capture device to modify the pixel by adjusting at least one of: exposure duration, gain, and bias for the pixel.

47. A computer program product for use in a light field image capture device, the light field image capture device including an aperture, a main lens, a microlens array, at least one sensor, and processing circuitry, the lenses on the microlens array arranged in a regular pattern, the pixels on the at least one sensor arranged in a regular pattern, the microlens array and at least one sensor interoperating to capture light field image data from light passing through the aperture and the main lens, the computer program product comprising at least one computer storage device having stored thereon computer-executable instructions that, when executed at a processor, cause the light field image capture device to:

access light that has passed through the aperture and the main leans;

introduce random variations into at least one of: the regular pattern of lenses in the microlens array and the regular pattern of pixels in the at least one sensor;

subsequent to introduction of the random variations, capture light field image data from the accessed light; and

send the captured light field image data to the processing circuitry.

48. A light field image capture device, comprising:

a microlens array;

at least one sensor, configured to capture light field image data representing output of the microlens array;

a pre-processor, configured to determine a read-out mode of the at least one sensor and to pre-process the captured light field image data in accordance with a the determined read-out mode to reduce the data size of the captured light field image data; and

processing circuitry, configured to process the pre-processed captured light field image data to generate visual output.

49. The device of claim 48, wherein the pre-processor is configured to pre-process the captured light field image data by:

processing at least one frame of the captured light field image data in accordance with the determined read-out mode; and

processing at least one other frame of the captured light field image data in accordance with a second different read-out mode.

50. A light field image capture device, comprising:

a microlens array;

at least one sensor, configured to capture light field image data representing output of the microlens array, the light field image data comprising a disk pattern formed on the sensor, the at least one sensor having a color filter array (CFA) grid layout;

a pre-processor, configured to access the configuration of the disk pattern and to determine how to modify the color filter array (CFA) to improve the quality of the color information captured from the output of the microlens array;

a CFA modifier, configured to modify the color filter array (CFA) in accordance with the determination; and

processing circuitry, configured to process the pre-processed light field image data to generate visual output;

wherein the disk pattern and the color filter array (CFA) interoperate to convert output from the microlens array into captured light field image data;

and wherein the at least one sensor captures light field image data from the output of the microlens array in accordance with the disk pattern and the modified color filter array (CFA).

51. A light field image capture device, comprising:

a microlens array;

at least one sensor, configured to capture light field image data representing output of the microlens array, the light field image data including properties for each of a plurality of pixels of the at least one sensor;

a pre-processor, configured to, for each of at least one pixel in the at least one sensor, and based on light coordinates of the at least one pixel, modify the pixel by adjusting at least one property of the pixel to compensate for non-uniform sampling due to other characteristics of the light field image capture device; and

processing circuitry, configured to process the pre-processed light field image data to generate visual output.

52. A light field image capture device, comprising:

an aperture;

a main lens;

a microlens array having lenses arranged in a regular pattern;

at least one sensor having pixels arranged in a regular pattern, the at least one sensor configured to capture light field image data representing output of the microlens array, the microlens array and the at least one sensor interoperating to capture light field image data from light passing through the aperture and the main lens:

a pre-processor, configured to access light that has passed through the aperture and the main leans and to introduce random variations into at least one of: the regular pattern of lenses in the microlens array and the regular pattern of pixels in the at least one sensor;

processing circuitry, configured to, subsequent to introduction of the random variations, capture light field image data from the accessed light and process the pre-processed light field image data to generate visual output.

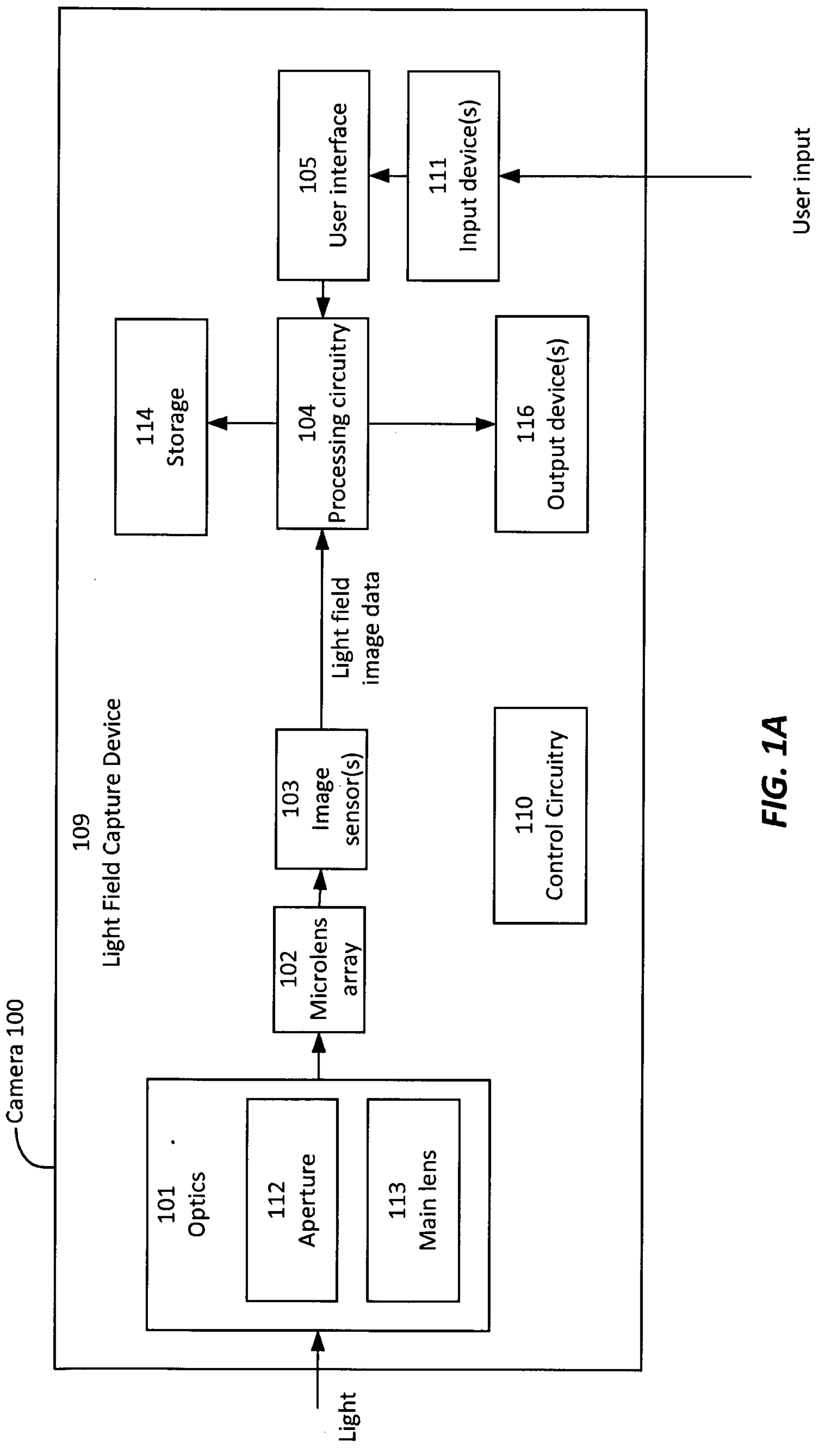

Camera 100
109
Light Field Capture Device
101
Optics
112
Aperture
113
Main lens
102
Microlens array
103
Image sensor(s)
Light field image data
104
Processing circuitry
114
Storage
116
Output device(s)
105
User interface
111
Input device(s)
110
Control Circuitry
Light
User input

FIG. 1A

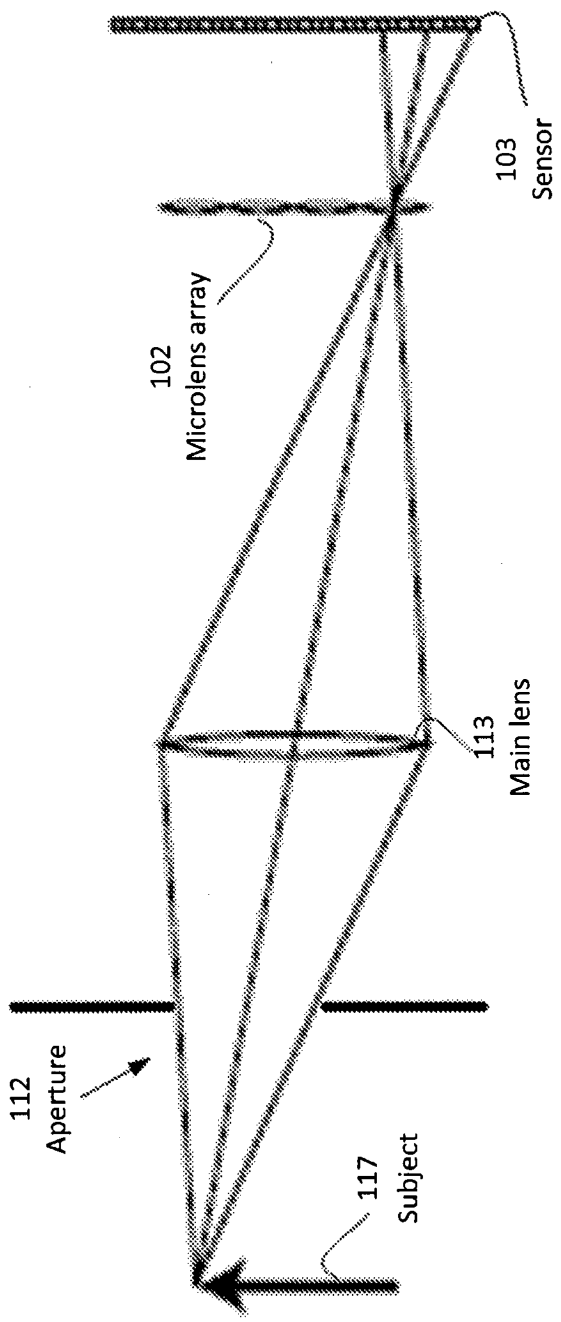

103
Sensor
102
Microlens array
113
Main lens
112
Aperture
117
Subject

FIG. 1B

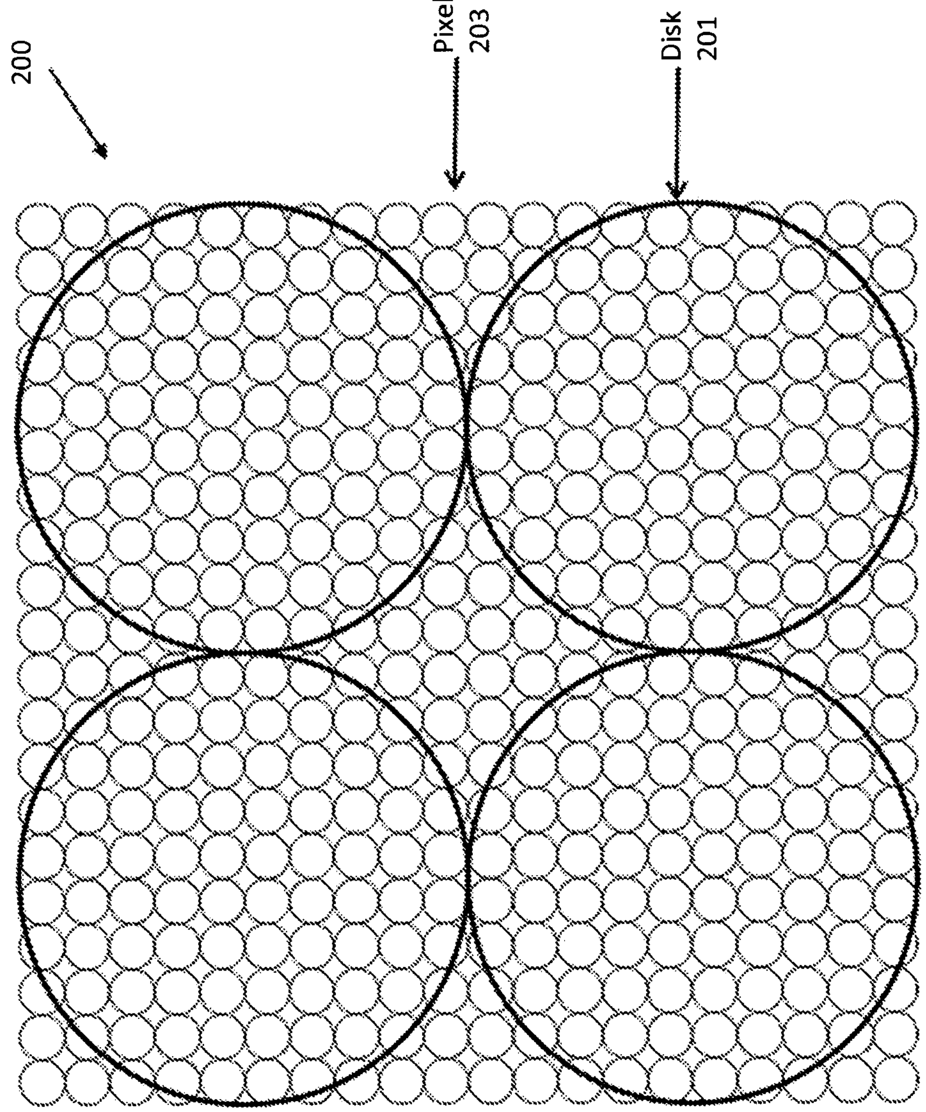


FIG. 2

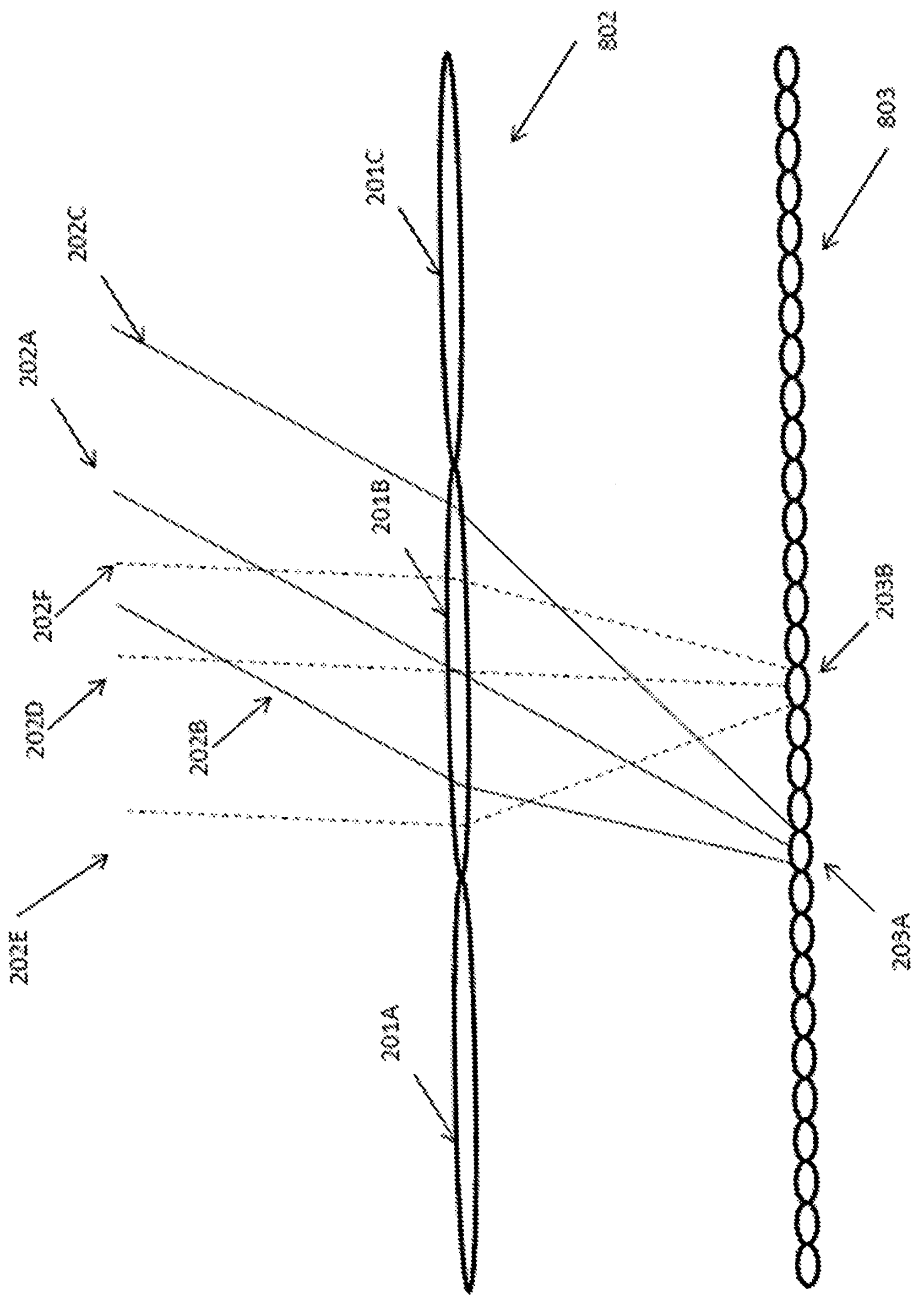

802
803
202C
201C
202A
201B
202F
202D
202B
202E
203B
203A
201A

FIG. 3A

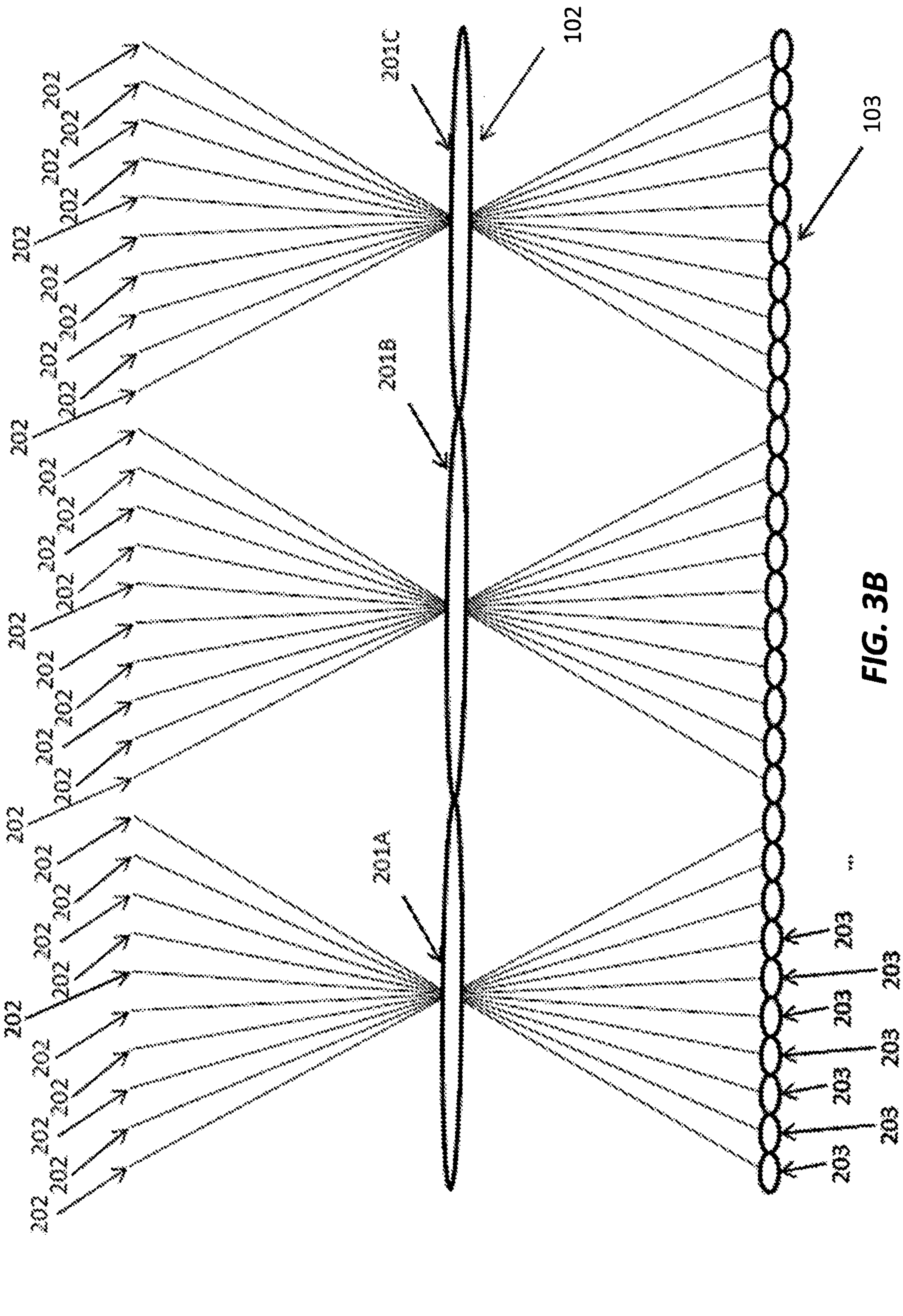


FIG. 3B

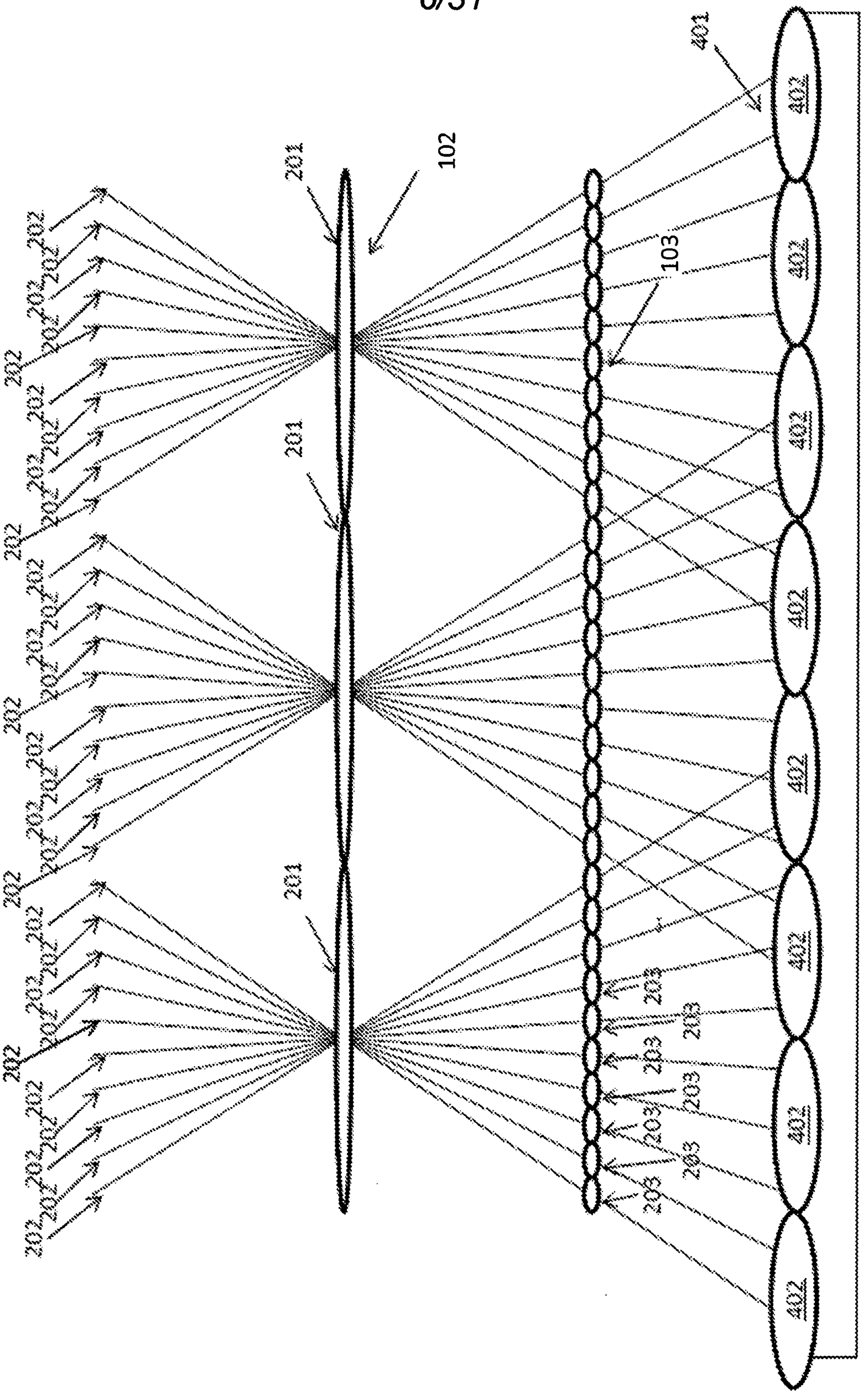


FIG. 4

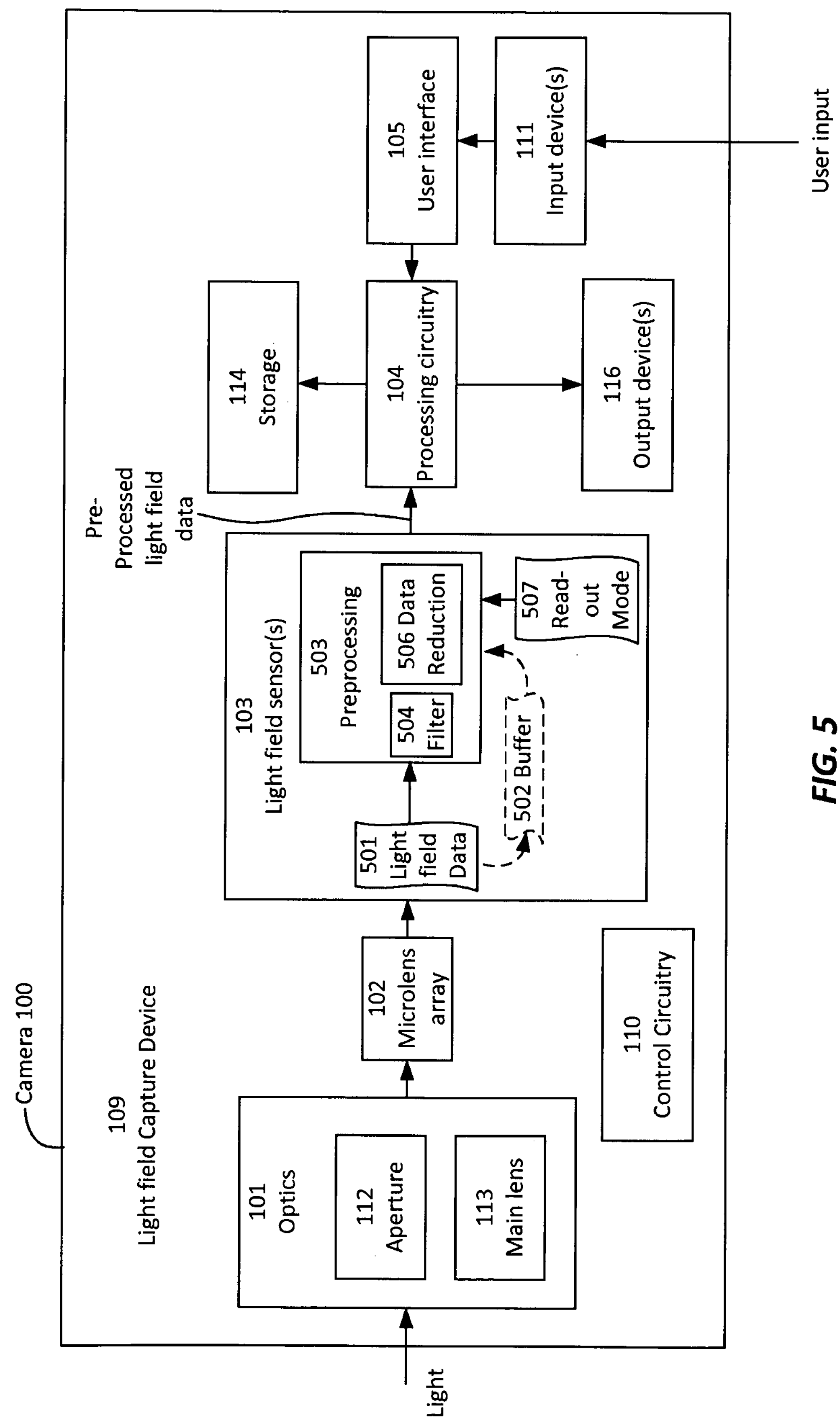

Camera 100
109
Light field Capture Device
101
Optics
112
Aperture
113
Main lens
102
Microlens array
103
Light field sensor(s)
501
Light field Data
502 Buffer
503
Preprocessing
504
Filter
506 Data Reduction
507
Read-out Mode
Pre-Processed light field data
114
Storage
104
Processing circuitry
116
Output device(s)
105
User interface
111
Input device(s)
110
Control Circuitry
Light
User input

FIG. 5

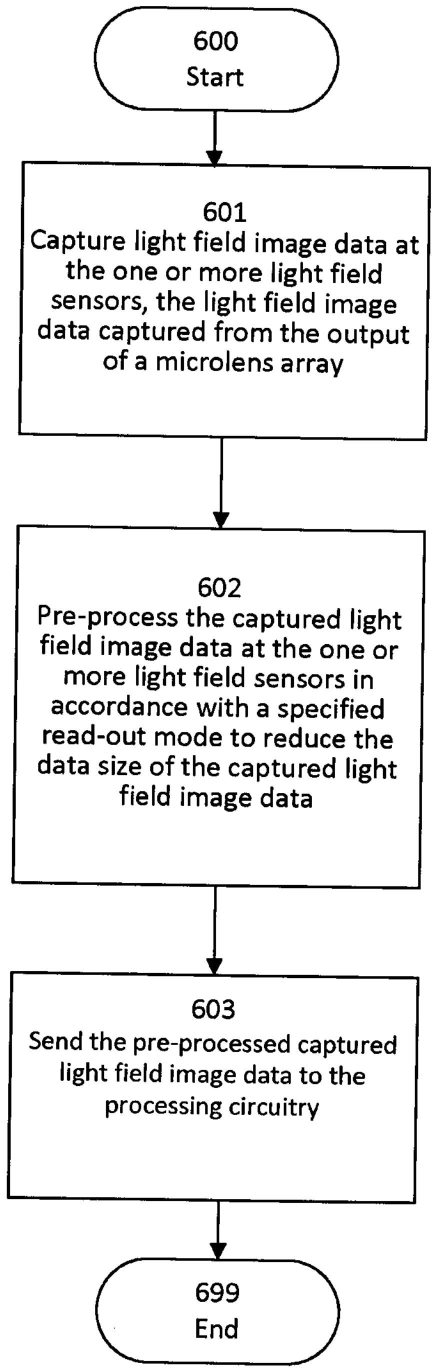

600
Start
601
Capture light field image data at the one or more light field sensors, the light field image data captured from the output of a microlens array
602
Pre-process the captured light field image data at the one or more light field sensors in accordance with a specified read-out mode to reduce the data size of the captured light field image data
603
Send the pre-processed captured light field image data to the processing circuitry
699
End

FIG. 6

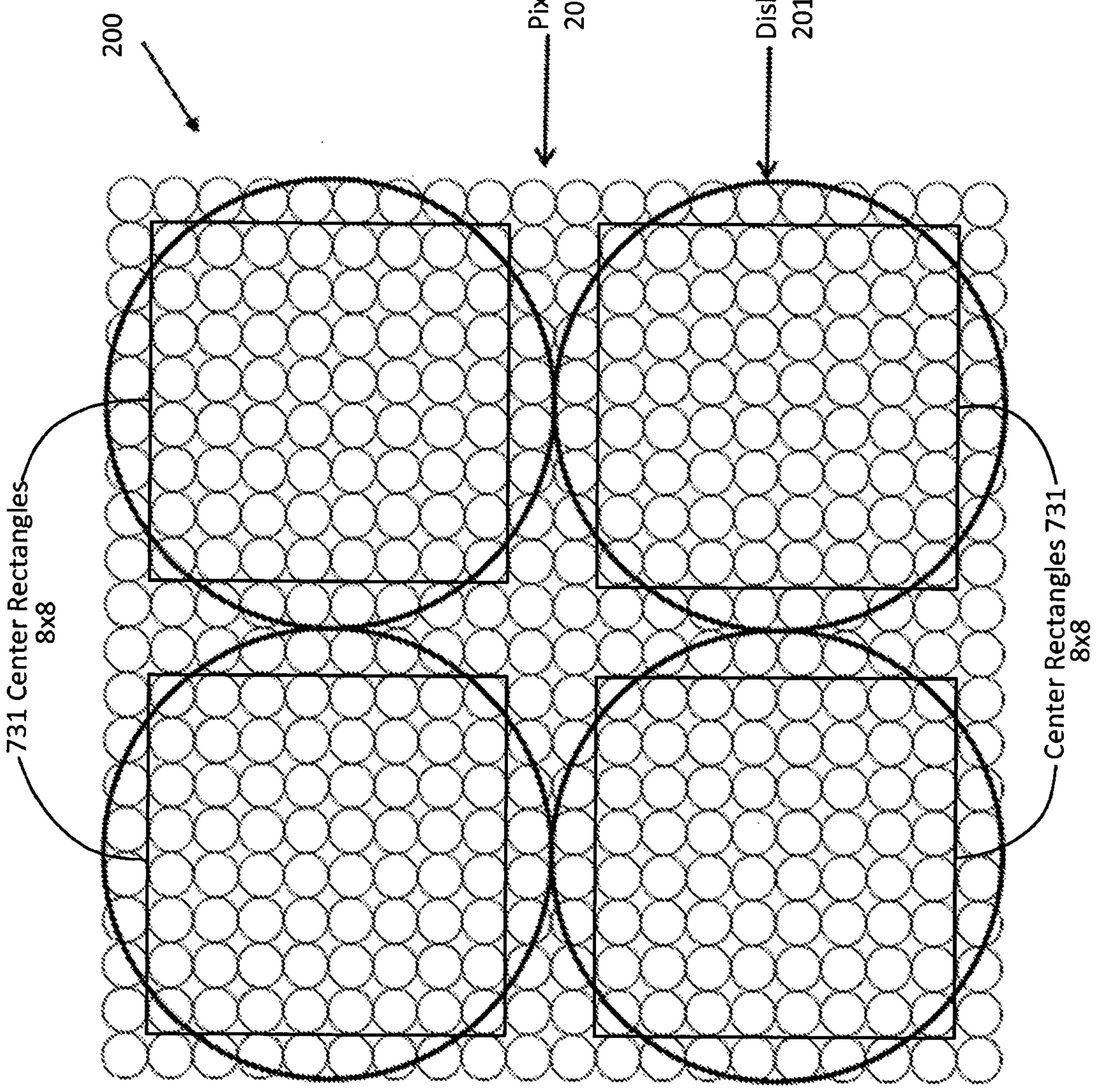

200
Pixel 203
Disk 201
731 Center Rectangles 8x8
Center Rectangles 731 8x8

FIG. 7

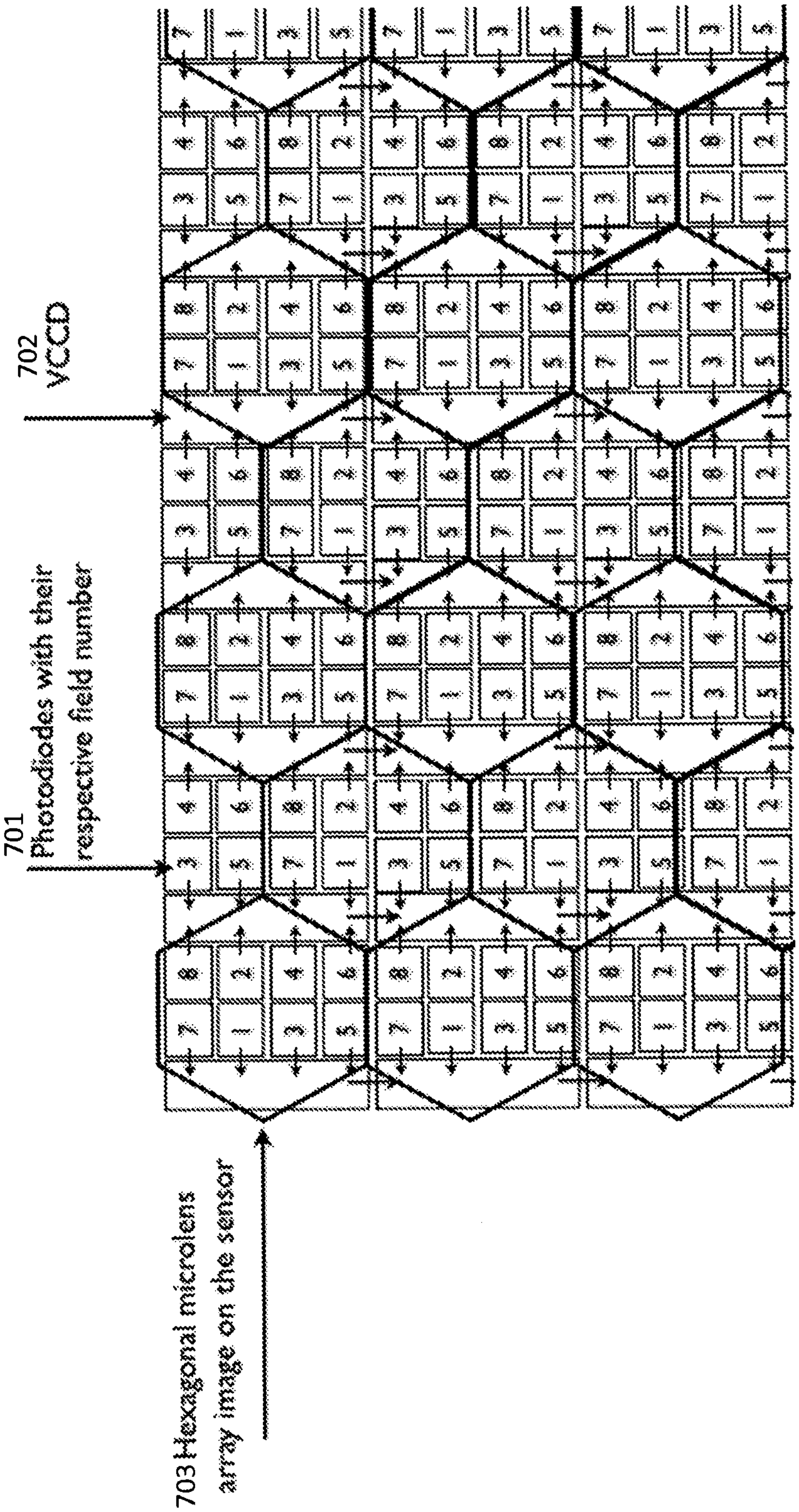

701 Photodiodes with their respective field number
702 VCCD
703 Hexagonal microlens array image on the sensor

FIG. 8

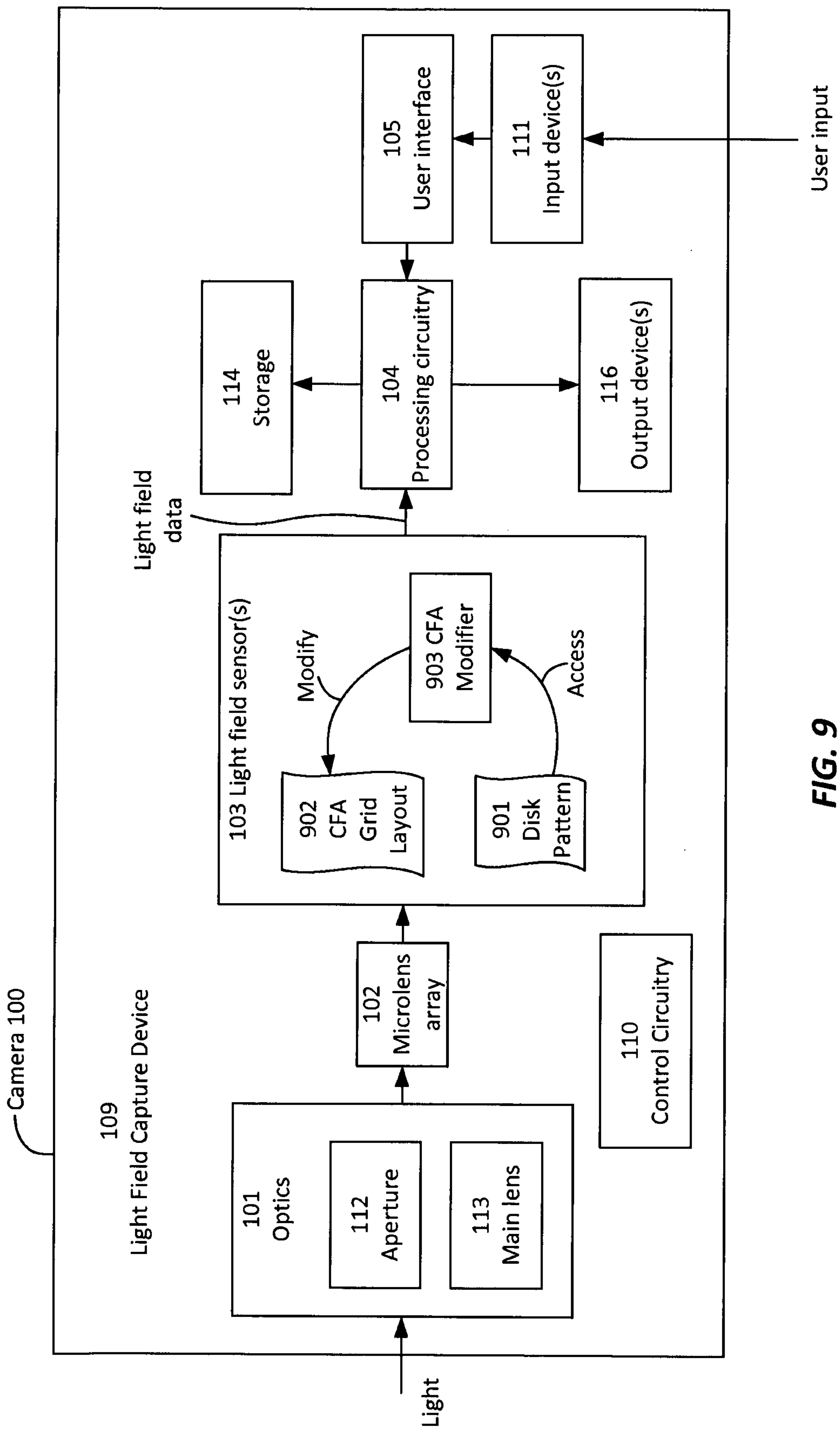

Camera 100
109
Light Field Capture Device
101
Optics
112
Aperture
113
Main lens
102
Microlens
array
103 Light field sensor(s)
902
CFA
Grid
Layout
901
Disk
Pattern
903 CFA
Modifier
Modify
Access
Light field
data
104
Processing circuitry
114
Storage
116
Output device(s)
105
User interface
111
Input device(s)
User input
110
Control Circuitry
Light

FIG. 9

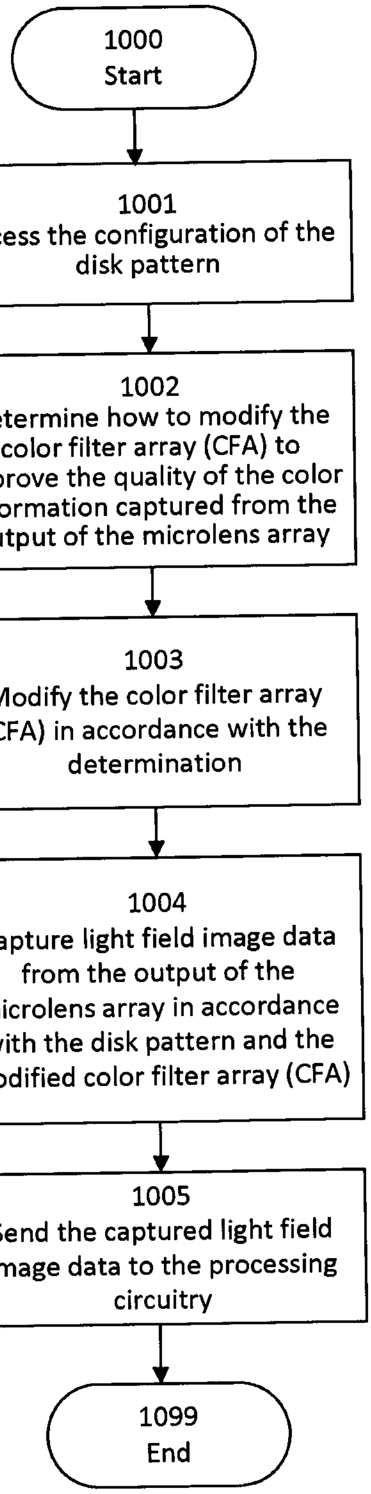

1000
Start
1001
Access the configuration of the disk pattern
1002
Determine how to modify the color filter array (CFA) to improve the quality of the color information captured from the output of the microlens array
1003
Modify the color filter array (CFA) in accordance with the determination
1004
Capture light field image data from the output of the microlens array in accordance with the disk pattern and the modified color filter array (CFA)
1005
Send the captured light field image data to the processing circuitry
1099
End

FIG. 10

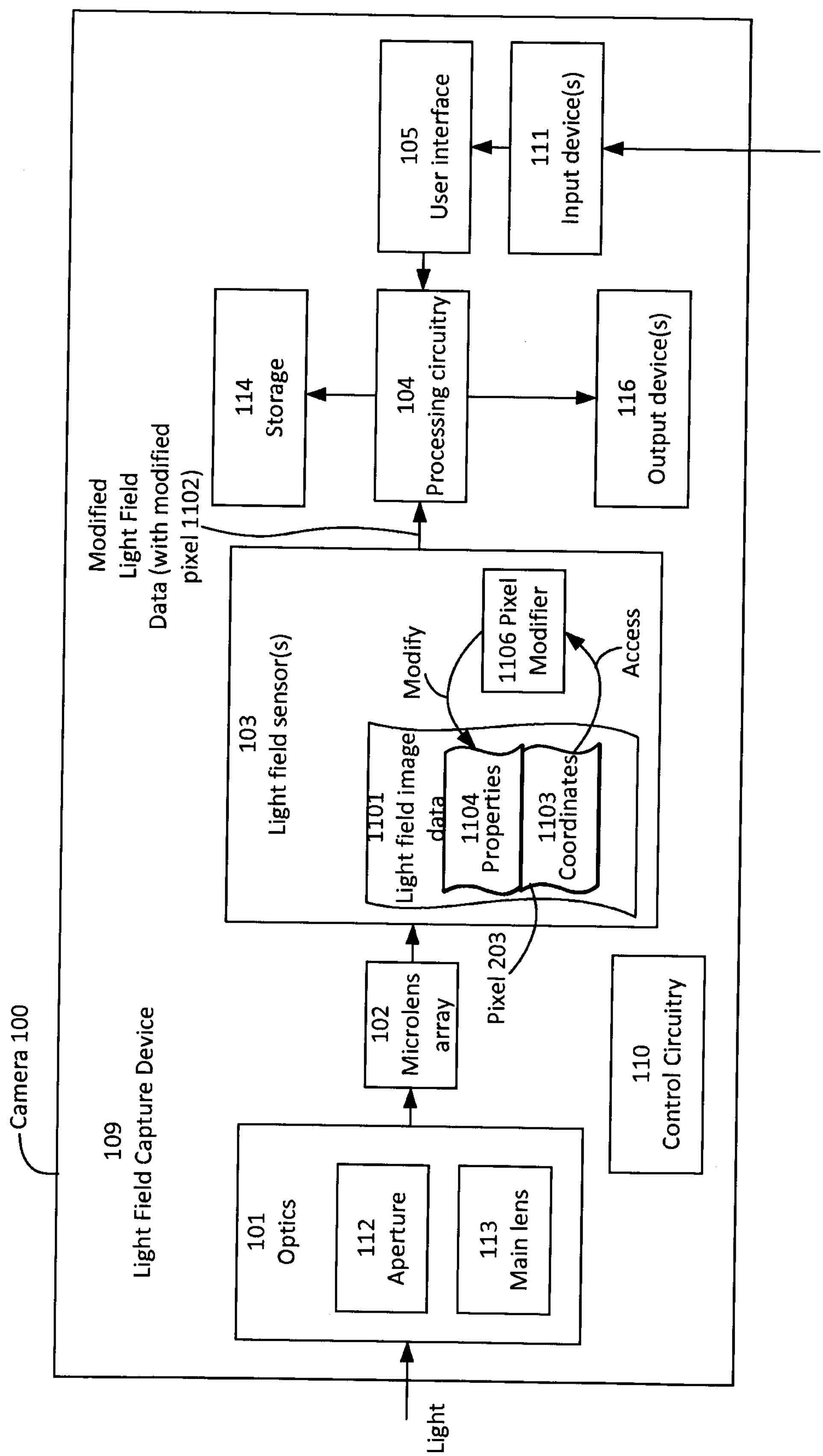

Camera 100
109
Light Field Capture Device
101
Optics
112
Aperture
113
Main lens
Light
102
Microlens array
103
Light field sensor(s)
1101
Light field image data
1104
Properties
1103
Coordinates
Pixel 203
1106 Pixel Modifier
Modify
Access
110
Control Circuitry
Modified Light Field Data (with modified pixel 1102)
114
Storage
104
Processing circuitry
116
Output device(s)
105
User interface
111
Input device(s)
User input

FIG. 11

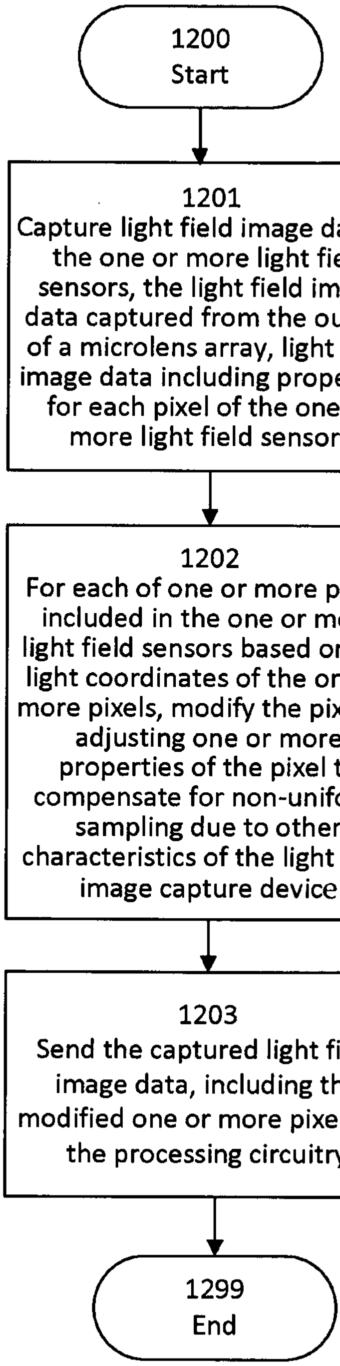

1200
Start
1201
Capture light field image data at the one or more light field sensors, the light field image data captured from the output of a microlens array, light field image data including properties for each pixel of the one or more light field sensors
1202
For each of one or more pixels included in the one or more light field sensors based on the light coordinates of the one or more pixels, modify the pixel by adjusting one or more properties of the pixel to compensate for non-uniform sampling due to other characteristics of the light field image capture device
1203
Send the captured light field image data, including the modified one or more pixels, to the processing circuitry
1299
End

FIG. 12

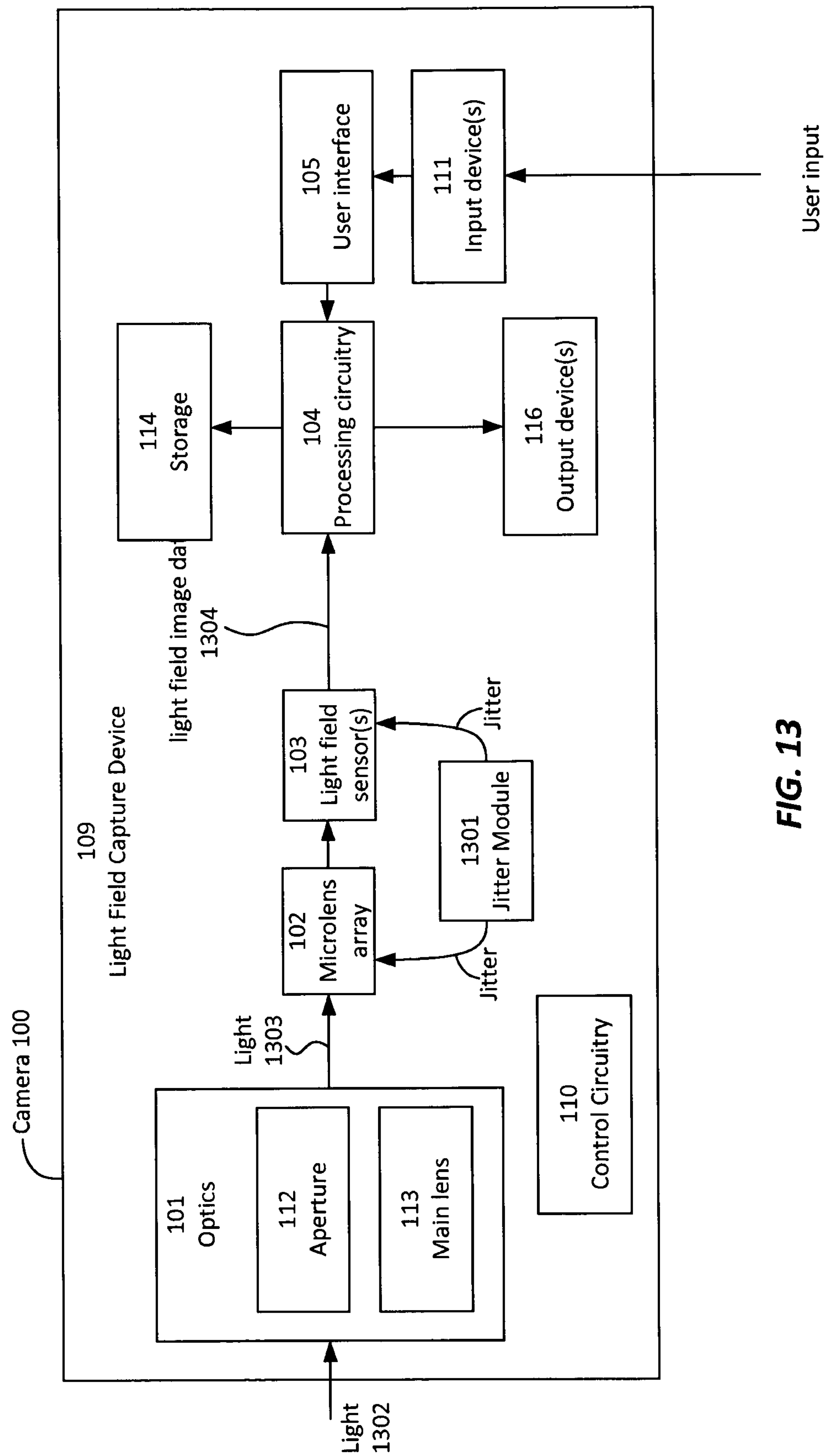

Camera 100
109
Light Field Capture Device
101
Optics
112
Aperture
113
Main lens
Light
1302
Light
1303
102
Microlens array
103
Light field sensor(s)
1301
Jitter Module
Jitter
Jitter
light field image da
1304
104
Processing circuitry
114
Storage
116
Output device(s)
105
User interface
111
Input device(s)
User input
110
Control Circuitry

FIG. 13

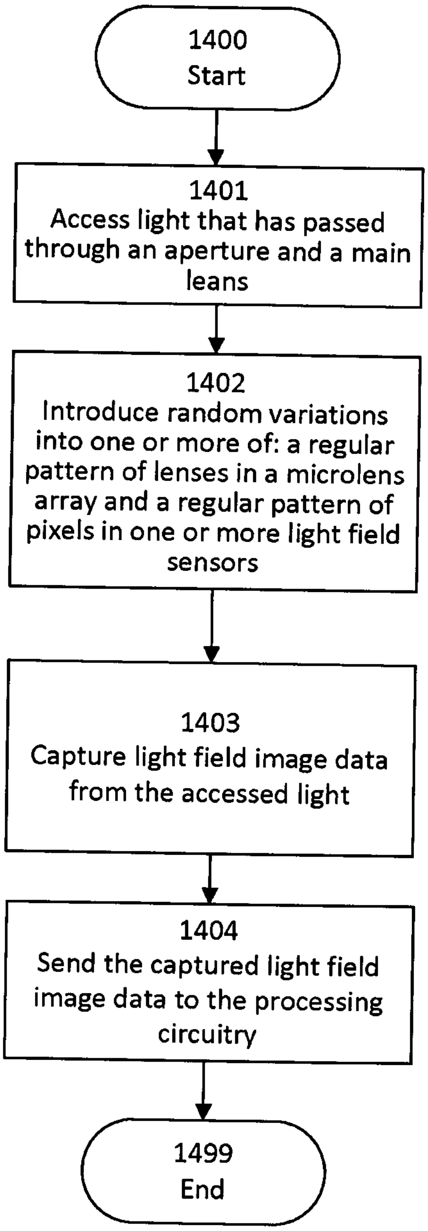

1400
Start
1401
Access light that has passed through an aperture and a main leans
1402
Introduce random variations into one or more of: a regular pattern of lenses in a microlens array and a regular pattern of pixels in one or more light field sensors
1403
Capture light field image data from the accessed light
1404
Send the captured light field image data to the processing circuitry
1499
End

FIG. 14

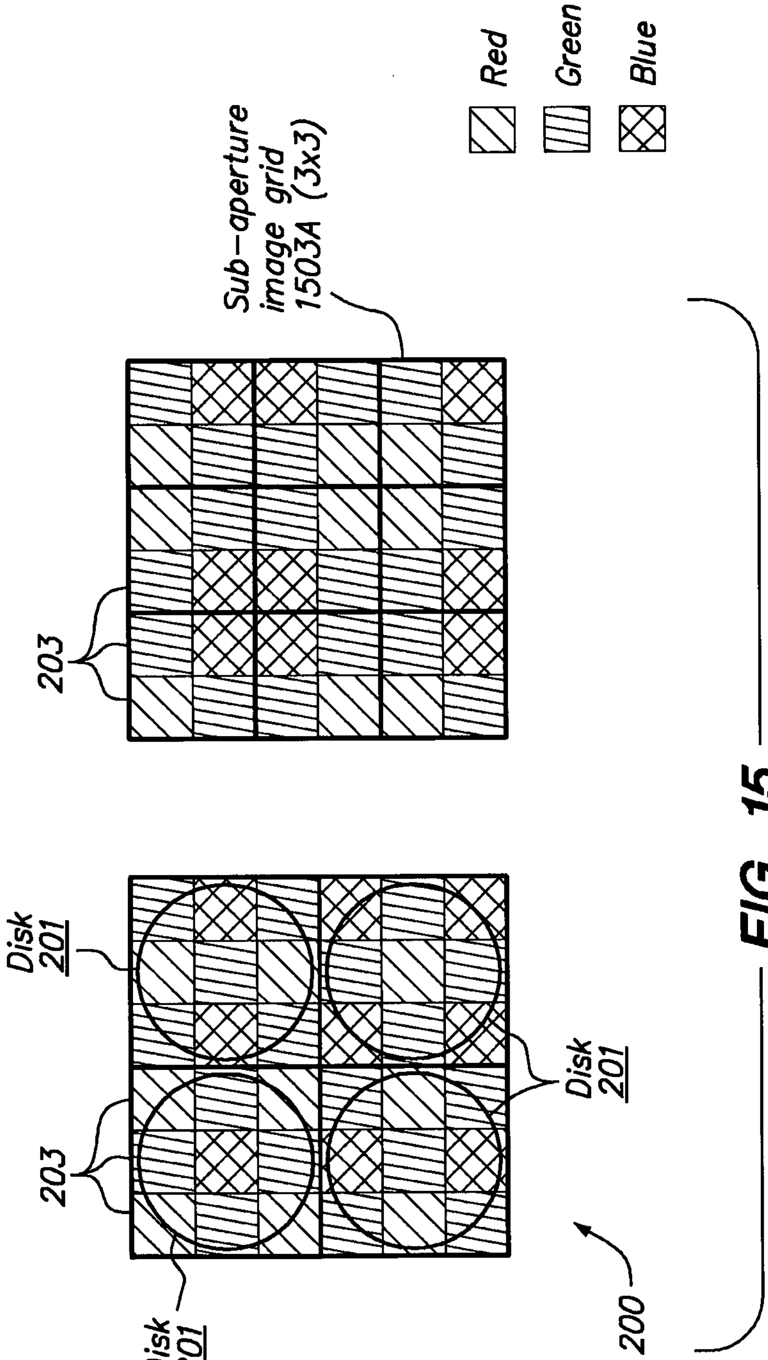

Sub-aperture image grid 1503A (3x3)
Red
Green
Blue
203
203
Disk 201
Disk 201
Disk 201
200

FIG. 15

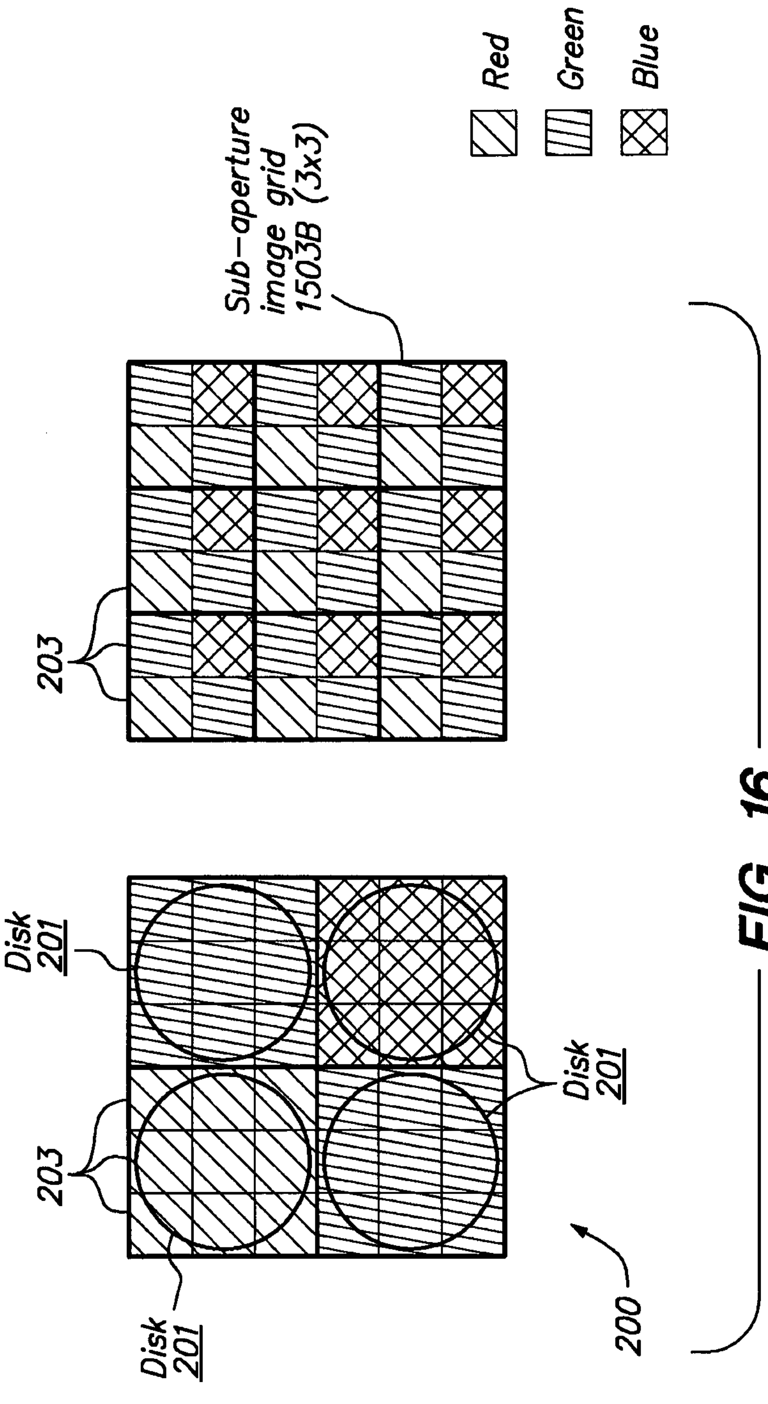

Sub-aperture
image grid
1503B (3x3)
Red
Green
Blue
203
Disk
201
203
Disk
201
Disk
201
200

FIG. 16

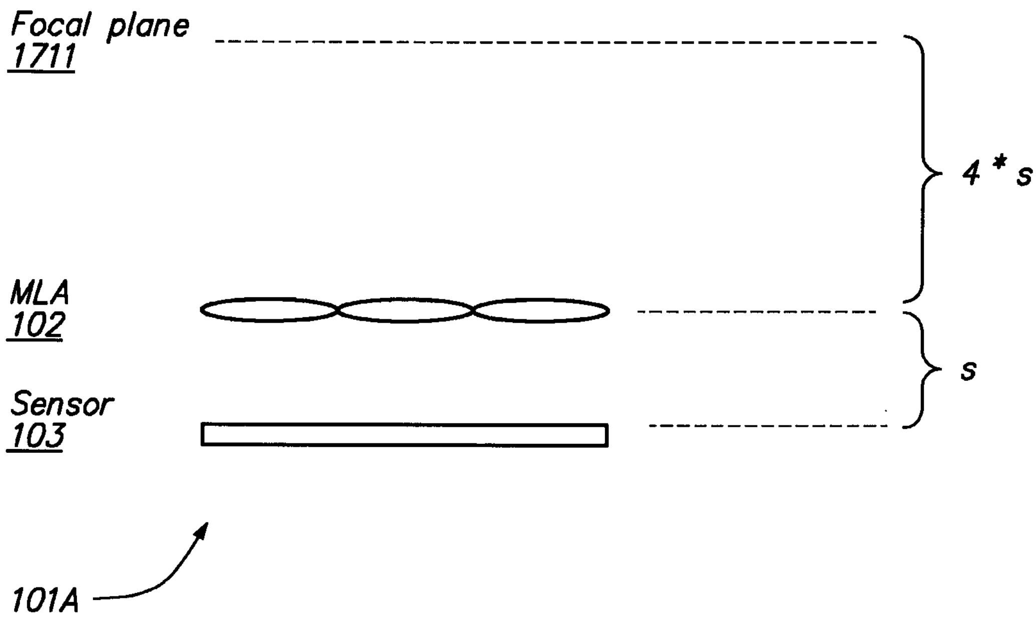


FIG. 17A

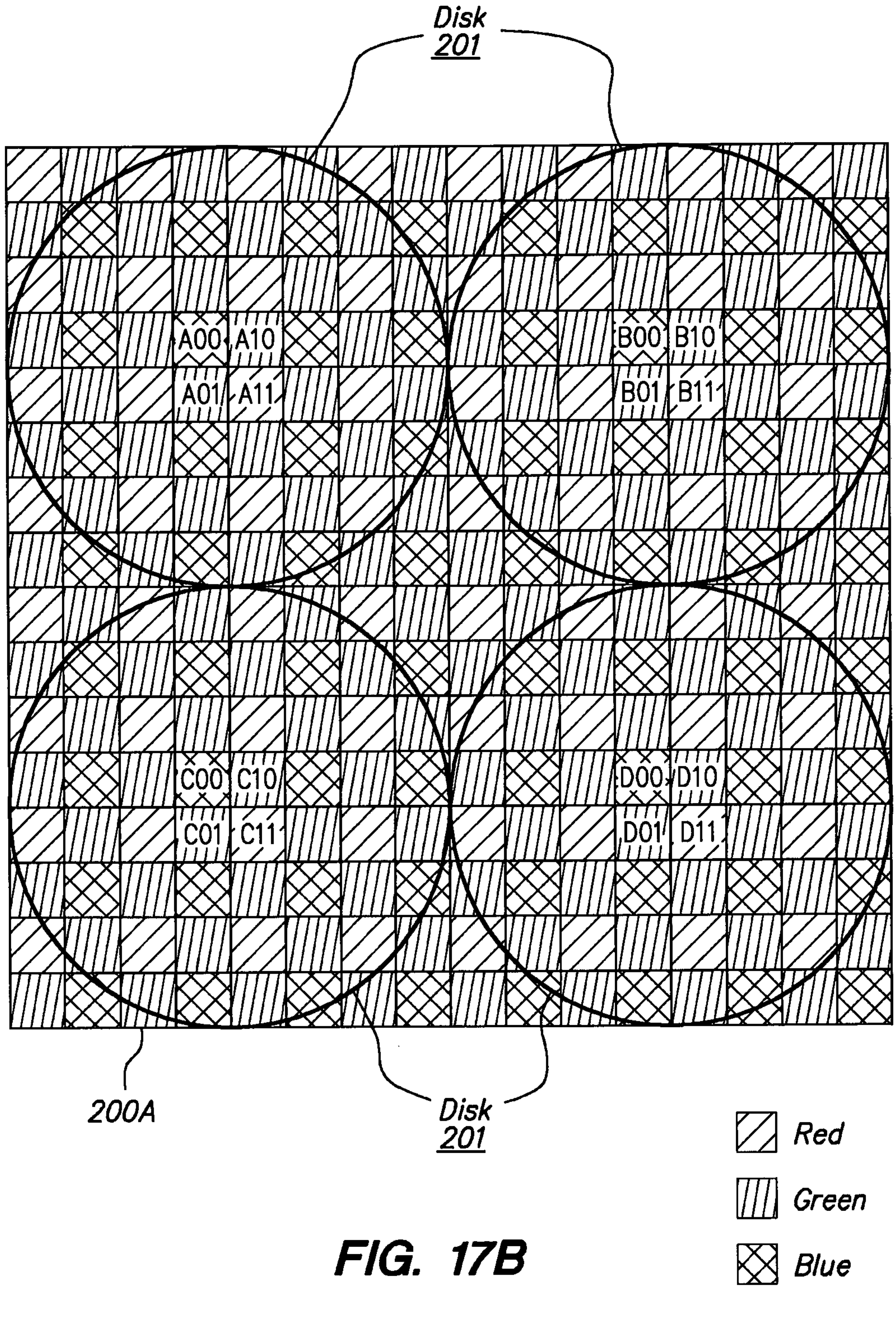

Disk
201
A00
A10
A01
A11
B00
B10
B01
B11
C00
C10
C01
C11
D00
D10
D01
D11
200A
Disk
201
Red
Green
Blue

FIG. 17B

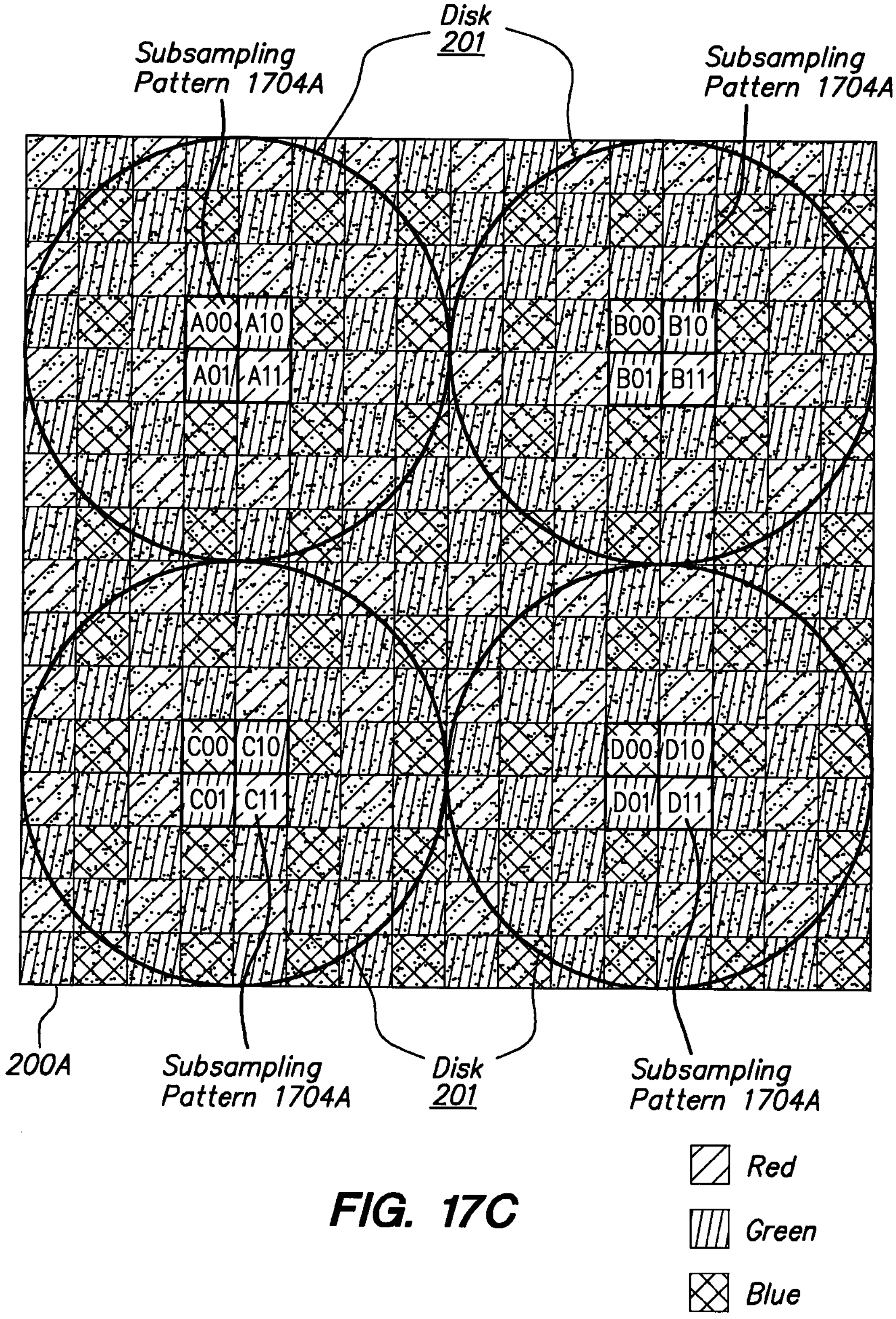

Disk
201
Subsampling
Pattern 1704A
Subsampling
Pattern 1704A
A00
A10
A01
A11
B00
B10
B01
B11
C00
C10
C01
C11
D00
D10
D01
D11
200A
Subsampling
Pattern 1704A
Disk
201
Subsampling
Pattern 1704A
Red
Green
Blue

FIG. 17C

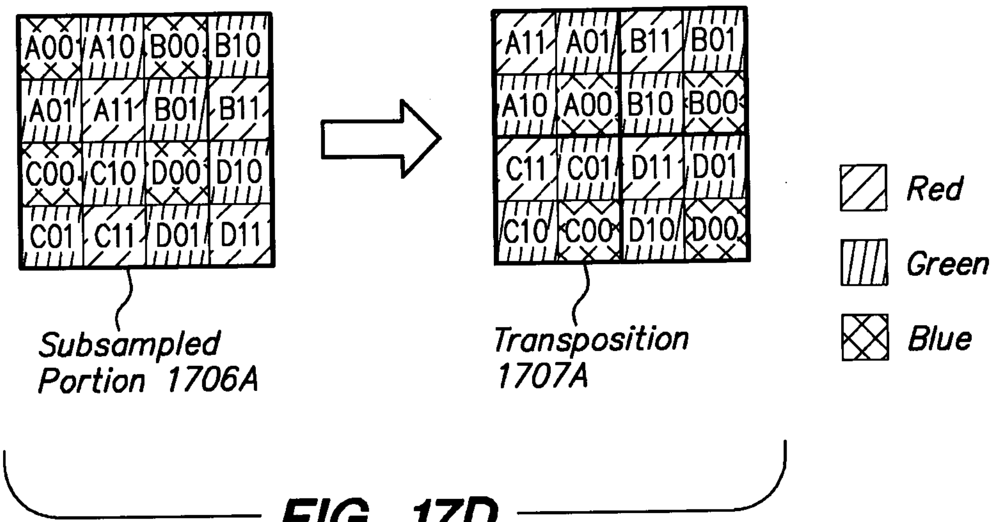

A00
A10
B00
B10
A01
A11
B01
B11
C00
C10
D00
D10
C01
C11
D01
D11
A11
A01
B11
B01
A10
A00
B10
B00
C11
C01
D11
D01
C10
C00
D10
D00
Subsampled Portion 1706A
Transposition 1707A
Red
Green
Blue

FIG. 17D

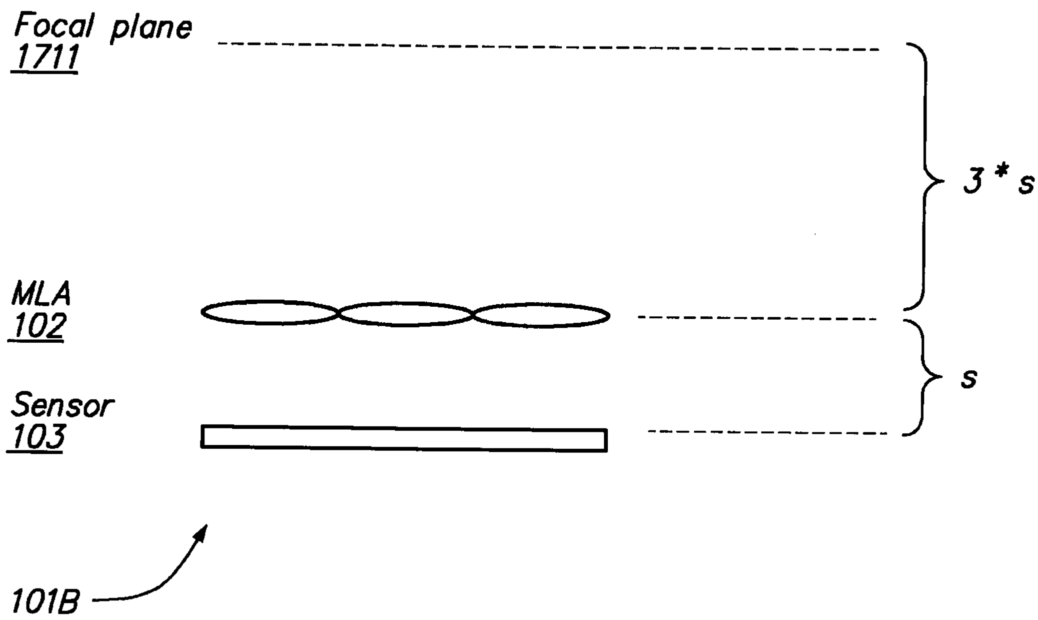


FIG. 18A

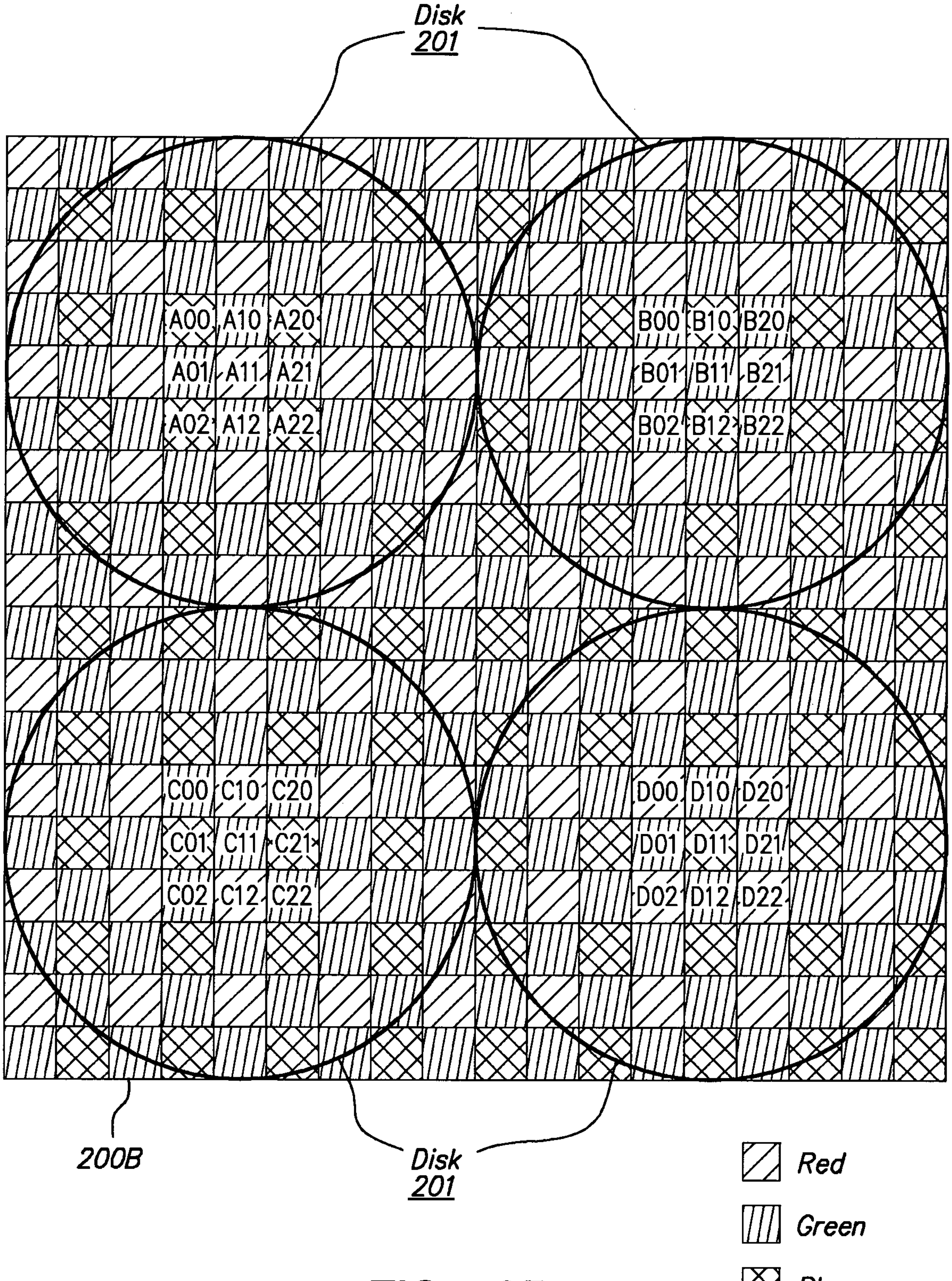

Disk
201
A00 A10 A20
A01 A11 A21
A02 A12 A22
B00 B10 B20
B01 B11 B21
B02 B12 B22
C00 C10 C20
C01 C11 C21
C02 C12 C22
D00 D10 D20
D01 D11 D21
D02 D12 D22
200B
Disk
201
Red
Green
Blue

FIG. 18B

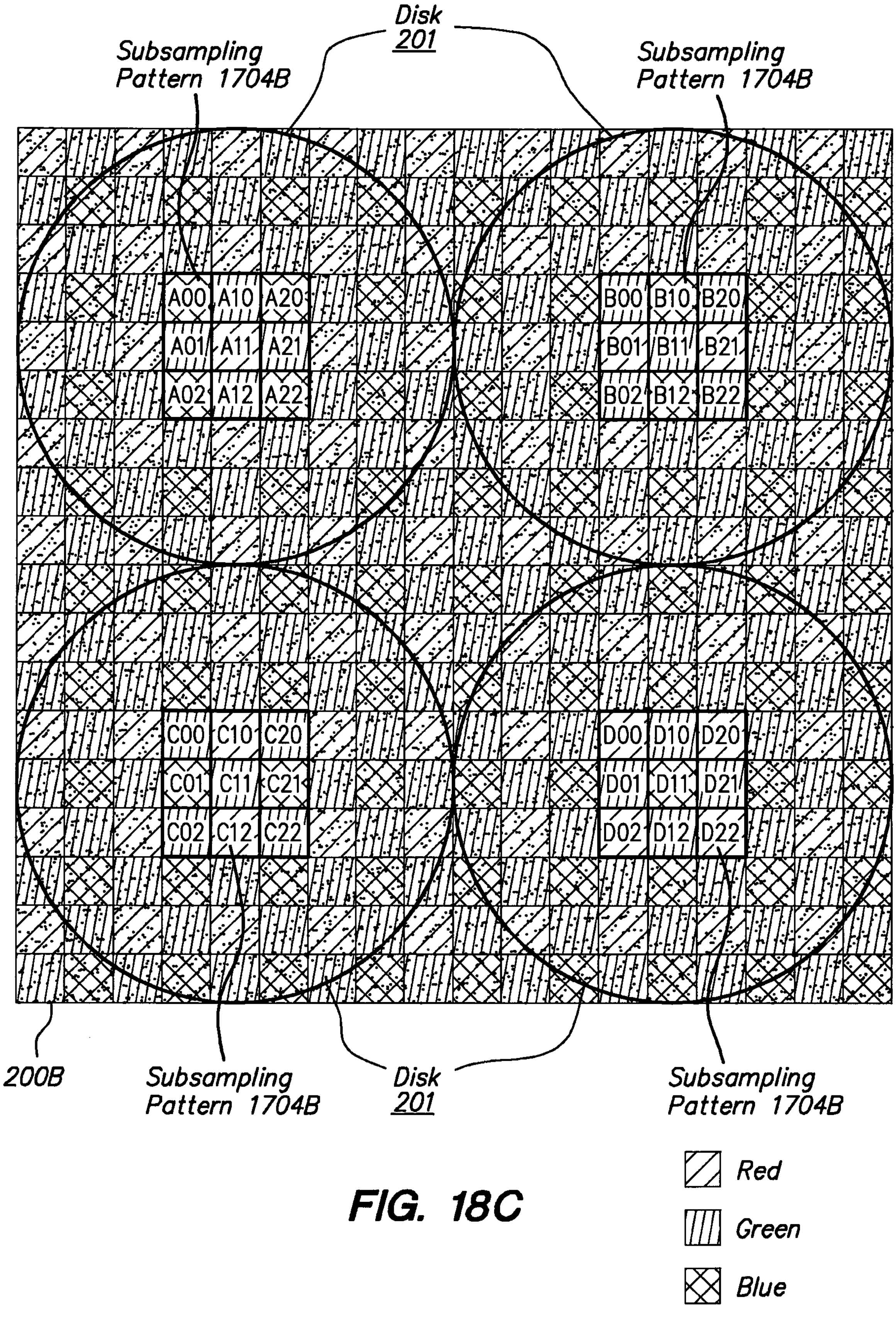

Disk
201
Subsampling
Pattern 1704B
Subsampling
Pattern 1704B
A00 A10 A20
A01 A11 A21
A02 A12 A22
B00 B10 B20
B01 B11 B21
B02 B12 B22
C00 C10 C20
C01 C11 C21
C02 C12 C22
D00 D10 D20
D01 D11 D21
D02 D12 D22
200B
Subsampling
Pattern 1704B
Disk
201
Subsampling
Pattern 1704B
Red
Green
Blue

FIG. 18C

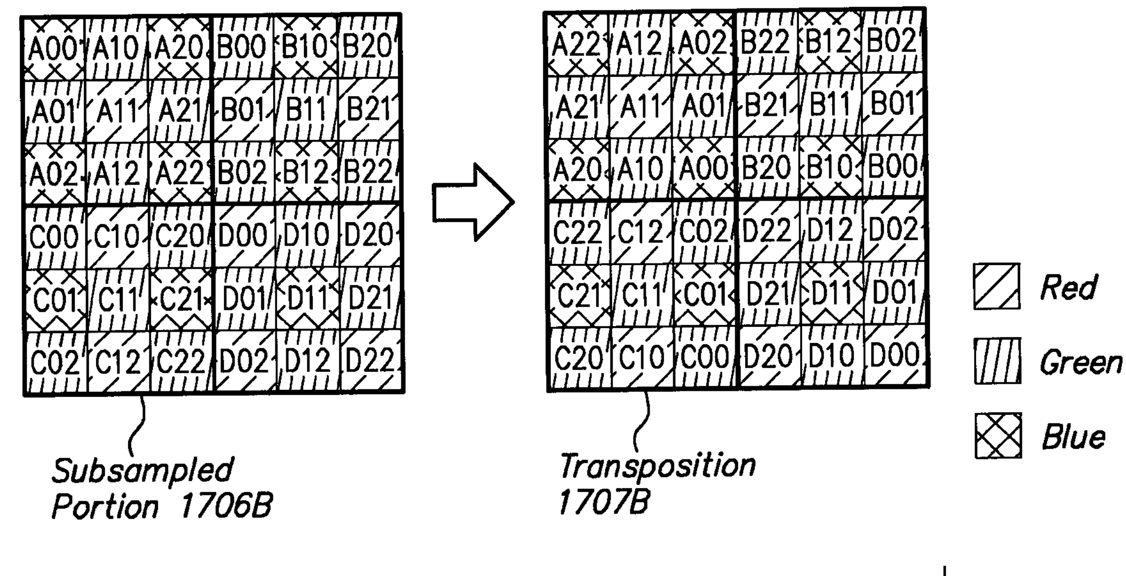

A00 A10 A20 B00 B10 B20
A01 A11 A21 B01 B11 B21
A02 A12 A22 B02 B12 B22
C00 C10 C20 D00 D10 D20
C01 C11 C21 D01 D11 D21
C02 C12 C22 D02 D12 D22
Subsampled Portion 1706B
A22 A12 A02 B22 B12 B02
A21 A11 A01 B21 B11 B01
A20 A10 A00 B20 B10 B00
C22 C12 C02 D22 D12 D02
C21 C11 C01 D21 D11 D01
C20 C10 C00 D20 D10 D00
Transposition 1707B
Red
Green
Blue

FIG. 18D

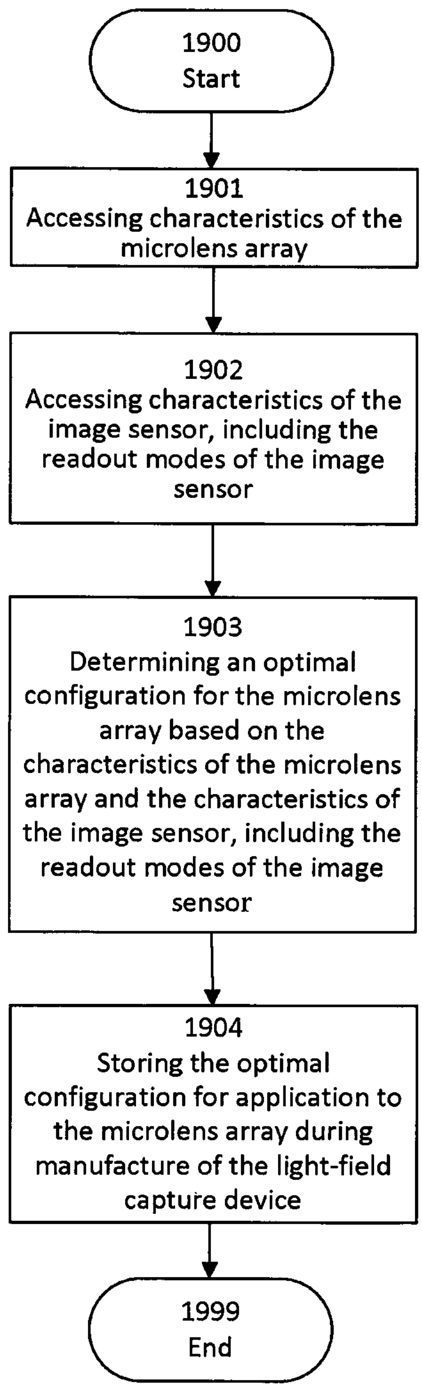

1900
Start
1901
Accessing characteristics of the microlens array
1902
Accessing characteristics of the image sensor, including the readout modes of the image sensor
1903
Determining an optimal configuration for the microlens array based on the characteristics of the microlens array and the characteristics of the image sensor, including the readout modes of the image sensor
1904
Storing the optimal configuration for application to the microlens array during manufacture of the light-field capture device
1999
End

FIG. 19

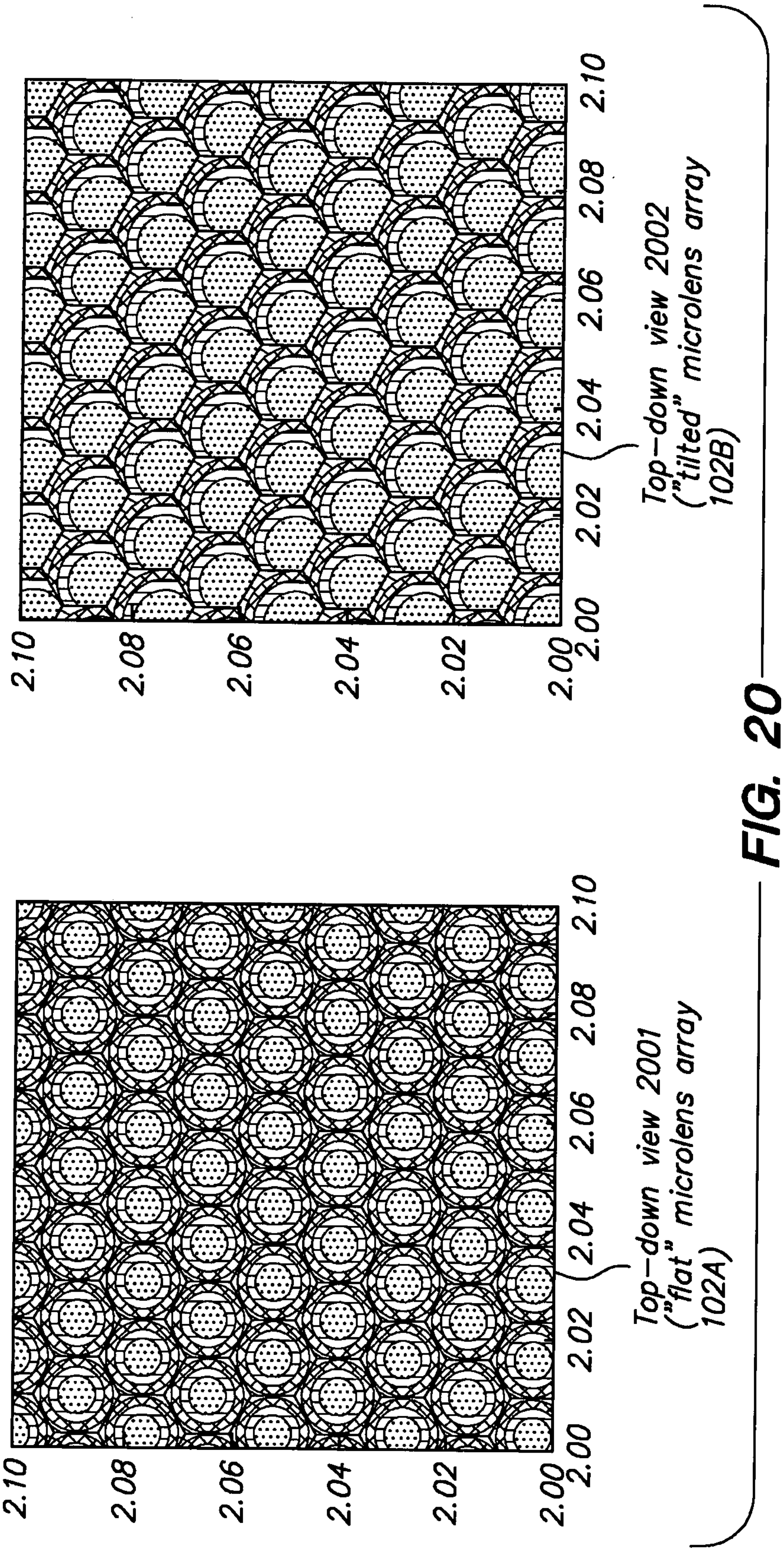
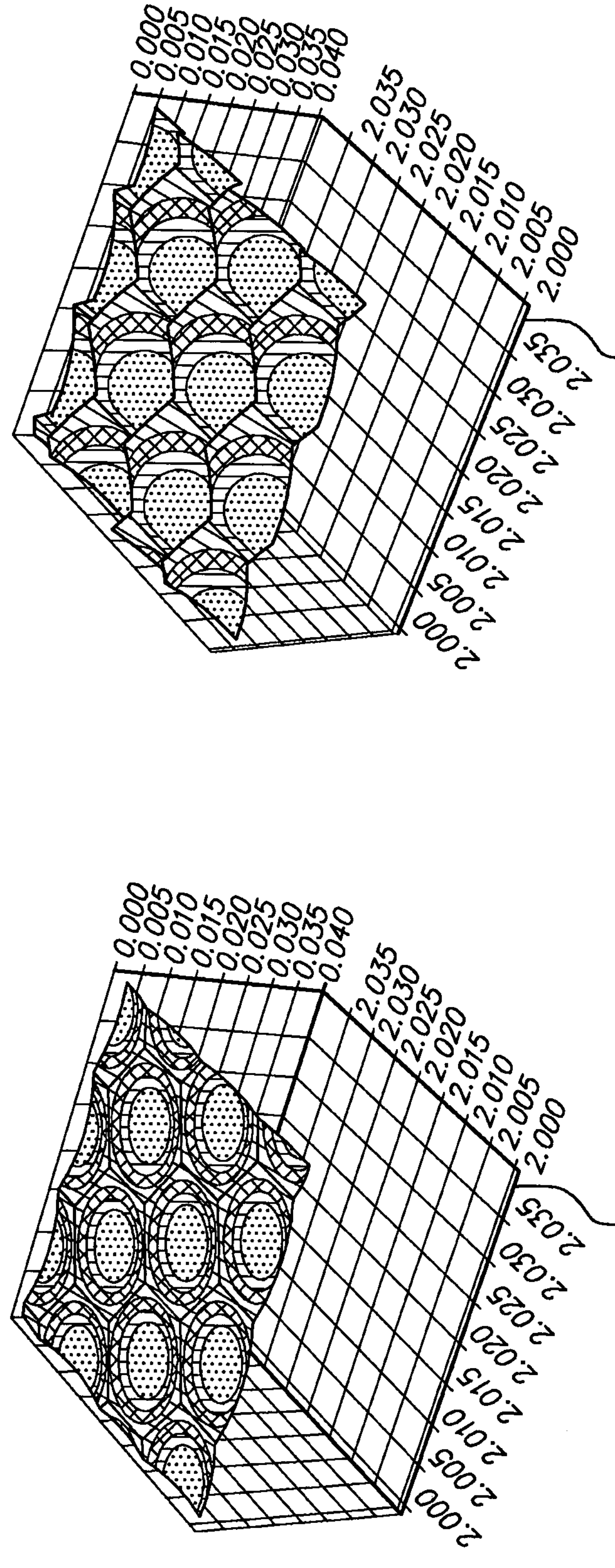

2.10
2.08
2.06
2.04
2.02
2.00
2.00
2.02
2.04
2.06
2.08
2.10
Top-down view 2002 ("tilted" microlens array 102B)
2.10
2.08
2.06
2.04
2.02
2.00
2.00
2.02
2.04
2.06
2.08
2.10
Top-down view 2001 ("flat" microlens array 102A)

FIG. 20



3D plot 2101B
("tilted" microlens array)

3D plot 2101A
("flat" microlens array)

FIG. 21

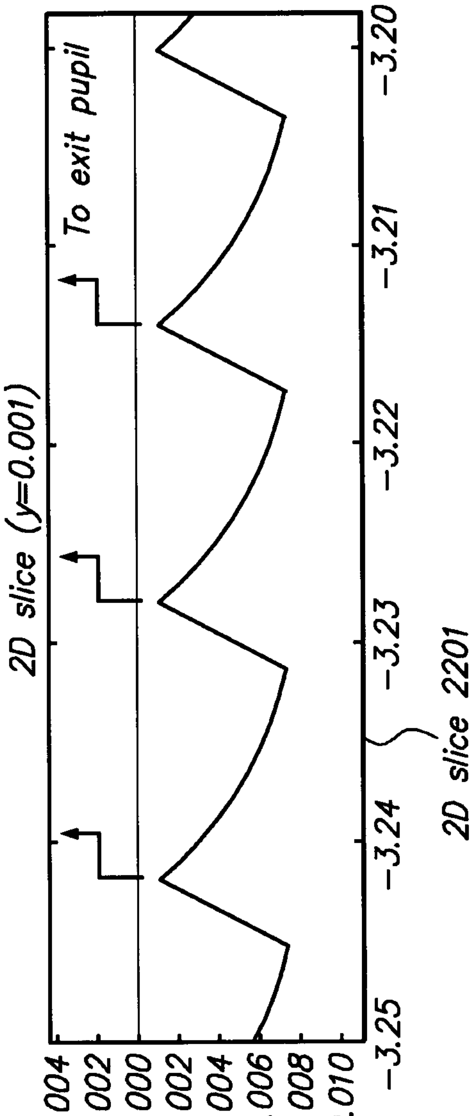

2D slice (y=0.001)
To exit pupil
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
−0.010
−3.25
−3.24
−3.23
−3.22
−3.21
−3.20
2D slice 2201

FIG. 22

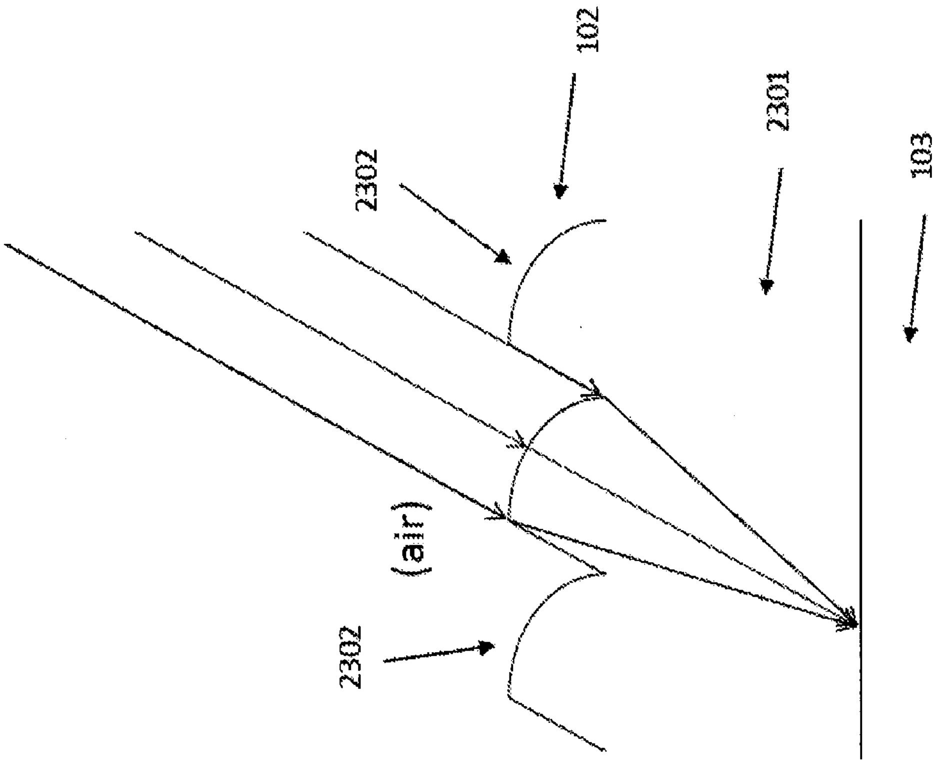


FIG. 23B

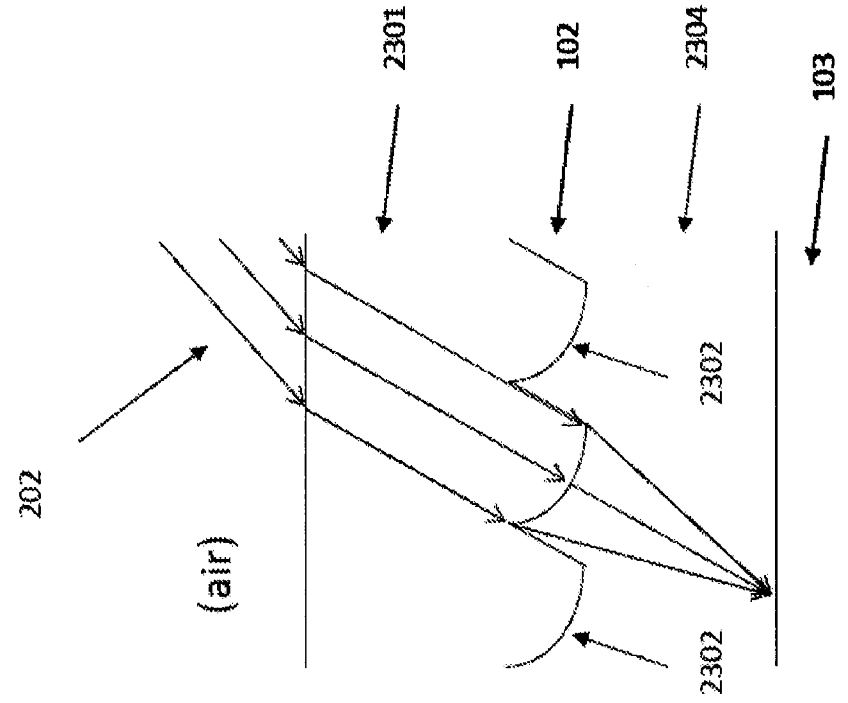


FIG. 23A

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/039760

A. CLASSIFICATION OF SUBJECT MATTER

H04N 5/225(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)
H04N 5/225; H04N 5/335; G06T 3/40; H04N 5/228

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: mode, pixel, processing and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7417670 B1 (LINZER ELLIOT N. et al.) 26 August 2008 See column 1, lines 12-19; column 3, lines 13-26; column 9, lines 4-59; and figures 5, 17, 18.	1-5,10-17,41-43 ,48-50
Y		28,29,33
A		6-9,18-27,30-32 ,34-40,44-47,51,52
Y	US 2011-0221947 A1 (AWAZU KOUHEI) 15 September 2011 See paragraphs [0053]-[0058] and figures 1, 2.	28,29,33
A	US 2008-0260291 A1 (ALAKARHU JUHA et al.) 23 October 2008 See paragraphs [0078]-[0082] and figure 8.	1-52
A	US 2010-0328485 A1 (IMAMURA KUNIHIRO et al.) 30 December 2010 See paragraphs [0101]-[0113] and figure 1.	1-52
A	US 2011-0205384 A1 (ZARNOWSKI JEFFREY JON et al.) 25 August 2011 See paragraphs [0112]-[0116] and figure 5.	1-52

☐ 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 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
30 September 2013 (30.09.2013)

Date of mailing of the international search report
01 October 2013 (01.10.2013)

Name and mailing address of the ISA/KR
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea
Facsimile No. +82-42-472-7140

Authorized officer
HWANG Yun Koo
Telephone No. +82-42-481-5715

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2013/039760

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 7417670 B1	26/08/2008	US 7893967 B1	22/02/2011
		US 7982788 B1	19/07/2011
US 2011-0221947 A1	15/09/2011	CN 102483510 A	30/05/2012
		EP 2362257 A1	31/08/2011
		EP 2362257 A4	03/10/2012
		JP 04764958 B2	07/09/2011
		US 8102460 B2	24/01/2012
		WO 2011-061998 A1	26/05/2011
US 2008-0260291 A1	23/10/2008	WO 2008-125936 A1	23/10/2008
US 2010-0328485 A1	30/12/2010	CN 101981917 A	23/02/2011
		JP 2009-246745 A	22/10/2009
		WO 2009-122468 A1	08/10/2009
US 2011-0205384 A1	25/08/2011	AU 2011-220563 A1	13/09/2012
		CA 2790714 A1	01/09/2011
		CA 2790853 A1	01/09/2011
		EP 2539854 A1	02/01/2013
		EP 2540077 A1	02/01/2013
		JP 2013-520936 A	06/06/2013
		JP 2013-520939 A	06/06/2013
		KR 10-2013-0008029 A	21/01/2013
		KR 10-2013-0009977 A	24/01/2013
		TW 201215164 A	01/04/2012
		US 2009-0290043 A1	26/11/2009
		US 2010-0149393 A1	17/06/2010
		US 8035711 B2	11/10/2011
		WO 2011-106461 A1	01/09/2011
		WO 2011-106568 A1	01/09/2011

(19) 中华人民共和国国家知识产权局

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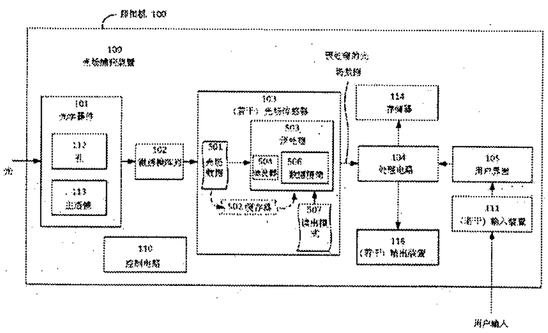
(54) 发明名称

用于改进的光场捕获和操作的光学系统的优化

(57) 摘要

根据本发明的各个实施例，光场捕获装置的光学系统被优化为以便改进捕获的光场图像数据。优化光场捕获装置的光学系统可以产生更加便宜和／或易于处理的捕获光场图像数据（静止的和视频）。光学系统可以被优化为在使用更加便宜的处理方法时产生改进的质量或分辨率，所述处理方法的计算成本适合各种处理和／或资源约束。因此，光场照相机的光学系统可以被优化以降低尺寸和／或成本，和／或提高这种光学系统的质量。



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1. 一种用于降低捕获的光场图像数据的大小的方法，在光场图像捕获装置中，所述光场图像捕获装置包括至少一个传感器和处理电路，所述处理电路被配置成处理捕获的光场图像数据以产生可视化输出，所述方法包括：

在所述至少一个传感器上捕获光场图像数据，所述光场图像数据代表微透镜阵列的输出；

确定所述至少一个传感器的读出模式；

根据确定的读出模式预处理所述捕获的光场图像数据以降低所述捕获的光场图像数据的数据大小；以及

将所述预处理的捕获光场图像数据发送到所述处理电路。

2. 根据权利要求 1 所述的方法，其中，预处理所述捕获光场图像数据包括执行从由下列组成的组中选择的至少一个：子采样、合并以及重采样所述捕获光场图像数据。

3. 根据权利要求 2 所述的方法，其中，预处理所述捕获光场图像数据包括在执行从由子采样、合并以及重采样所述捕获光场图像数据组成的组中选择的至少一个之前，对所述捕获光场图像数据进行滤波。

4. 根据权利要求 1 所述的方法，其中，预处理所述捕获光场图像数据包括基于所述至少一个像素的光场坐标，跳过在所述至少一个传感器上的至少一个像素。

5. 根据权利要求 1 所述的方法，进一步包括在预处理所述捕获光场图像数据之前：

在所述至少一个传感器上的本地存储器中缓存所述捕获光场图像数据中的至少一部分；以及

从所述本地存储器中访问所述捕获光场图像数据中的所述至少一部分。

6. 根据权利要求 1 所述的方法，其中，根据确定的读出模式预处理所述捕获光场图像数据包括根据在逐像素基础上配置的读出模式处理所述捕获光场图像数据。

7. 根据权利要求 6 所述的方法，其中，根据在逐像素基础上配置的读出模式处理所述捕获光场图像数据包括使用以下当中的至少一个：

位掩码；

至少一个位掩码瓦片；

至少一个权重图像瓦片；以及

逐像素偏置；

在逐像素基础上处理像素。

8. 根据权利要求 1 所述的方法，其中，预处理所述捕获光场图像数据包括基于在所述至少一个传感器上的至少一个像素的光场坐标，使用可变位深和可变像素最大值中的至少一个。

9. 根据权利要求 1 所述的方法，其中，预处理所述捕获光场图像数据包括对所述光场图像数据执行光场图像感知处理。

10. 根据权利要求 1 所述的方法，其中，预处理所述捕获光场图像数据包括：

根据确定的读出模式处理所述捕获光场图像数据中的至少一个帧；以及

根据第二个不同的读出模式处理所述捕获光场图像数据中的至少一个其它的帧。

11. 根据权利要求 1 所述的方法，其中，预处理所述捕获光场图像数据包括在多个不同的读出周期中从缓存器中读出所述捕获光场图像数据。

12. 根据权利要求 1 所述的方法，其中，所述至少一个传感器包括电荷耦合装置 CCD 图像传感器，并且其中，根据特定的读出模式预处理所述捕获光场图像数据包括使用所述电荷耦合装置 CCD 图像传感器执行所述特定的读出模式。

13. 根据权利要求 12 所述的方法，其中，使用所述电荷耦合装置 CCD 图像传感器执行所述特定的读出模式包括使用电荷耦合装置 CCD 图像传感器借助隔行扫描执行分辨率降低的读出模式。

14. 一种用于修改彩色滤波阵列 CFA 的方法，在光场图像捕获装置中，所述光场图像捕获装置包括微透镜阵列、至少一个传感器、在所述传感器上形成的圆盘图案、彩色滤波阵列 CFA 栅格布局和处理电路，所述处理电路被配置成处理捕获的光场图像数据以产生可视化输出，所述圆盘图案和所述彩色滤波阵列 CFA 交互操作以将来自所述微透镜阵列的输出转换成捕获光场图像数据，所述方法包括：

访问所述圆盘图案的配置；

确定如何修改所述彩色滤波阵列 CFA 以提高从所述微透镜阵列的输出捕获的色彩信息的质量；

根据确定结果修改所述彩色滤波阵列 CFA；

根据所述硬盘图案和所述修改的彩色滤波阵列 CFA 从所述微透镜阵列的输出捕获光场图像数据；以及

将所述捕获光场图像数据发送到所述处理电路。

15. 根据权利要求 14 所述的方法，其中，根据确定结果修改所述彩色滤波阵列 CFA 包括修改所述彩色滤波阵列，使得不向至少一个像素施加任何彩色滤波器。

16. 根据权利要求 14 所述的方法，其中，根据确定结果修改所述彩色滤波阵列 CFA 包括修改至少一个像素的彩色滤波器通带。

17. 根据权利要求 14 所述的方法，其中，根据确定结果修改所述彩色滤波阵列 CFA 包括随机化彩色滤波阵列 CFA 图案。

18. 一种用于修改至少一个传感器的像素属性的方法，在光场图像捕获装置中，所述光场图像捕获装置包括至少一个传感器和处理电路，所述处理电路被配置成处理捕获的光场图像数据以产生可视化输出，所述方法包括：

在所述至少一个传感器上捕获光场图像数据，所述光场图像数据代表微透镜阵列的输出；所述光场图像数据包括所述至少一个传感器的多个像素中每一个像素的属性；

对于所述至少一个传感器中的至少一个像素中的每个像素，基于所述至少一个像素的光坐标，通过调节所述像素的至少一个属性来修改所述像素以补偿由于所述光场图像捕获装置的其它特征造成的不均匀采样；以及

将所述捕获光场图像数据，包括修改的至少一个像素，发送到所述处理电路。

19. 根据权利要求 18 所述的方法，其中，通过调节所述像素的至少一个属性来修改所述像素以补偿由于所述光场图像捕获装置的其它特征造成的不均匀采样包括调节所述像素的至少一个属性，以补偿与以下当中的至少一个相关的因素：图像传感器角响应、微透镜阵列和主透镜。

20. 根据权利要求 18 所述的方法，其中，通过调节所述像素的至少一个属性来修改所述像素以补偿由于所述光场图像捕获装置的其它特征造成的不均匀采样包括调节以下当

中的至少一个：所述像素的曝光时间、增益和偏置。

21. 根据权利要求 18 所述的方法，其中，通过调节所述像素的至少一个属性来修改所述像素以补偿由于所述光场图像捕获装置的其它特征造成的不均匀采样包括使用以下当中的至少一个执行像素调节：半导体的制造后位置修整、数字或模拟信号、以及将比例或偏置熔合到半导体中。

22. 一种用于扰乱光场图像捕获装置的至少一个规则图案以提高捕获光场图像数据的质量的方法，在光场图像捕获装置中，所述光场图像捕获装置包括孔、主透镜、微透镜阵列、至少一个传感器和处理电路，所述微透镜阵列上的透镜排列成规则图案，所述至少一个传感器上的像素排列成规则图案，所述微透镜阵列和至少一个传感器交互操作以从通过所述孔和所述主透镜的光中捕获光场图像数据，所述方法包括：

获取通过所述孔和所述主透镜的光；

向以下当中的至少一个引入随机变化：所述微透镜阵列中的透镜的规则图案和所述至少一个传感器中的像素的规则图案；

在引入所述随机变化之后，从所述获取的光中捕获光场图像数据；以及

将所述捕获光场图像数据发送到所述处理电路。

23. 根据权利要求 22 所述的方法，其中，将随机变化引入到透镜的规则图案和像素的规则图案中的至少一个包括将抖动图案引入到透镜的规则图案和像素的规则图案中的至少一个。

24. 根据权利要求 23 所述的方法，其中，将抖动图案引入到透镜的规则图案和像素的规则图案中的至少一个包括将抖动图案引入到在整个微透镜阵列上延伸的透镜的规则图案中。

25. 根据权利要求 23 所述的方法，其中，将抖动图案引入到透镜的规则图案和像素的规则图案中的至少一个包括将抖动图案引入到在整个至少一个传感器上延伸的像素的规则图案中。

26. 根据权利要求 23 所述的方法，其中，将抖动图案引入到透镜的规则图案和像素的规则图案中的至少一个包括将抖动图案瓦片引入到透镜的规则图案中，所述抖动图案瓦片在整个微透镜阵列上重复多次。

27. 根据权利要求 23 所述的方法，其中，将抖动图案引入到透镜的规则图案和像素的规则图案中的至少一个包括将抖动图案瓦片引入到像素的规则图案中，所述抖动图案瓦片在整个至少一个传感器上重复多次。

28. 一种光学系统，包括：

主透镜；

微透镜阵列，所述微透镜阵列包括多个微透镜；以及

至少一个图像传感器，每个图像传感器具有多个像素；

其中，所述主透镜、所述微透镜阵列和所述至少一个图像传感器被配置并相对于彼此设置成使得一个或多个光图像传感器上的圆盘图像的水平间距和垂直间距中的至少一个等于整数个像素。

29. 根据权利要求 28 所述的光学系统，其中，所述主透镜、所述微透镜阵列和所述至少一个图像传感器被配置并相对于彼此设置成使得所述圆盘图像是 NxN 个像素的正方形栅

格。

30. 根据权利要求 29 所述的光学系统，其中，所述主透镜、所述微透镜阵列和所述一个或多个光图像传感器被配置并相对于彼此设置成使得光场图像数据的圆盘表示的阵列置换成所述光场图像数据的子孔径图像表示的等效阵列。

31. 根据权利要求 30 所述的光学系统，其中，所述主透镜、所述微透镜阵列和所述一个或多个光图像传感器被配置并被设置成将光场图像数据的圆盘表示的阵列置换成原始域数据和全色数据中至少一个上的光场图像数据的子孔径图像表示的等效阵列。

32. 根据权利要求 30 所述的光学系统，其中，所述主透镜、所述微透镜阵列和所述一个或多个光图像传感器被配置成并设置成将光场图像数据重新排序成直接地解释为 2D 图像的重新排序光场图像数据。

33. 根据权利要求 28 所述的光学系统，其中，所述微透镜阵列具有六角形布局。

34. 一种用于确定用于微透镜阵列的配置的方法，所述微透镜阵列定位在图像传感器上以用在光场图像捕获装置中，所述方法包括：

访问所述微透镜阵列的特征；

访问所述图像传感器的特征，包括所述图像传感器的读出模式；

基于所述微透镜阵列的特征和所述图像传感器的特征，包括所述图像传感器的读出模式，确定用于所述微透镜阵列的最理想配置；以及

存储所述最理想配置以在所述光场图像捕获装置的制造过程中应用到所述微透镜阵列。

35. 根据权利要求 34 所述的方法，其中，确定所述微透镜阵列的最理想配置包括确定所述微透镜阵列在所述图像传感器上的最理想位置。

36. 根据权利要求 34 所述的方法，其中，确定所述微透镜阵列的最理想配置包括确定所述微透镜阵列在所述图像传感器上的最理想取向。

37. 根据权利要求 34 所述的方法，其中，确定所述微透镜阵列的最理想配置包括考虑所述微透镜阵列关于与所述图像传感器正交的轴线的至少一个物理旋转。

38. 根据权利要求 34 所述的方法，其中，确定所述微透镜阵列的最理想配置包括考虑所述微透镜阵列在与所述图像传感器平面平行的平面内的至少一个物理平移。

39. 根据权利要求 34 所述的方法，其中，确定所述微透镜阵列的最理想配置包括考虑所述传感器的至少一个读出模式。

40. 根据权利要求 39 所述的方法，其中，每个读出模式是从由以下组成的组中选择的：合并、跳过、重采样和调整。

41. 一种用在光场图像捕获装置中的计算机程序产品，所述光场图像捕获装置包括至少一个传感器和处理电路，所述处理电路被配置成处理捕获的光场图像数据以产生可视化输出，所述计算机程序产品用于执行降低捕获的光场图像数据的大小的方法，所述计算机程序产品包括至少一个计算机存储装置，所述计算机存储装置上具有存储的计算机可执行指令，该指令当在处理器上执行时，引起所述光场图像捕获装置：

在所述至少一个传感器上捕获光场图像数据，所述光场图像数据代表微透镜阵列的输出；

确定所述至少一个传感器的读出模式；

根据确定的读出模式预处理所述捕获光场图像数据以降低所述捕获光场图像数据的数据大小；以及

将所述预处理的捕获光场图像数据发送到所述处理电路。

42. 根据权利要求 41 所述的计算机程序产品，其中，所述计算机程序产品被配置成引起所述光场图像捕获装置通过以下步骤预处理所述捕获光场图像数据：

根据所述确定的读出模式处理所述捕获光场图像数据的至少一个帧；以及

根据第二个不同的读出模式处理所述捕获光场图像数据的至少一个其它的帧。

43. 一种用在光场图像捕获装置中的计算机程序产品，所述光场图像捕获装置包括微透镜阵列、至少一个传感器、在所述传感器上形成的圆盘图案、彩色滤波阵列 CFA 栅格布局和处理电路，所述处理电路被配置成处理捕获的光场图像数据以产生可视化输出，所述圆盘图案和所述彩色滤波阵列 CFA 交互操作以将来自所述微透镜阵列的输出转换成捕获的光场图像数据，所述计算机程序产品包括至少一个计算机存储装置，所述计算机存储装置上具有存储的计算机可执行指令，所述指令当在处理器上执行时引起所述光场图像捕获装置：

访问所述圆盘图案的配置；

确定如何修改彩色滤波阵列 CFA 以提高从所述微透镜阵列的输出捕获的色彩信息的质量；

根据所述确定结果修改所述彩色滤波阵列 CFA；

根据所述圆盘图案和所述修改的彩色滤波阵列 CFA 从所述微透镜阵列的输出捕获光场图像数据；以及

将捕获的光场图像数据发送到所述处理电路。

44. 一种用在光场图像捕获装置中的计算机程序产品，所述光场图像捕获装置包括至少一个传感器和处理电路，所述处理电路被配置成处理捕获的光场图像数据以产生可视化输出，所述计算机程序产品包括至少一个计算机存储装置，所述计算机存储装置上具有存储的计算机可执行指令，所述指令当在处理器上执行时引起所述光场图像捕获装置：

在所述至少一个传感器上捕获光场图像数据，所述光场图像数据代表微透镜阵列的输出；所述光场图像数据包括所述至少一个传感器的多个像素中每一个像素的属性；

对于所述至少一个传感器中的至少一个像素中的每个像素，基于所述至少一个像素的光坐标，通过调节所述像素的至少一个属性来修改所述像素以补偿由于所述光场图像捕获装置的其它特征造成的不均匀采样；以及

将所述捕获光场图像数据，包括所述修改的至少一个像素，发送到所述处理电路。

45. 根据权利要求 44 所述的计算机程序产品，其中，所述计算机程序产品被配置成引起所述光场图像捕获装置通过调节所述像素的至少一个属性来修改所述像素，以补偿与图像传感器角响应、微透镜阵列和主透镜中的至少一个相关的因素。

46. 根据权利要求 44 所述的计算机程序产品，其中，所述计算机程序产品被配置成引起所述光场图像捕获装置通过调节所述像素的曝光时间、增益和偏置中的至少一个来修改所述像素。

47. 一种用在光场图像捕获装置中的计算机程序产品，所述光场图像捕获装置包括孔、主透镜、微透镜阵列、至少一个传感器和处理电路，所述微透镜阵列上的透镜排列成规则图

案，所述至少一个传感器上的像素排列成规则图案，所述微透镜阵列和至少一个传感器交互操作以从通过所述孔和所述主透镜的光中捕获光场图像数据，所述计算机程序产品包括至少一个计算机存储装置，所述计算机存储装置上具有存储的计算机可执行指令，所述指令在处理器上执行时引起所述光场图像捕获装置：

获取穿过所述孔和所述主透镜的光；

将随机变化引入到以下当中的至少一个：所述微透镜阵列中的透镜的规则图案和所述至少一个传感器中的像素的规则图案；

在引入所述随机变化之后，从所述获取的光中捕获光场图像数据；以及

将所述捕获光场图像数据发送到所述处理电路。

48. 一种光场图像捕获装置，包括：

微透镜阵列；

至少一个传感器，所述传感器被配置成捕获代表所述微透镜阵列的输出的光场图像数据；

预处理器，所述预处理器被配置成确定所述至少一个传感器的读出模式，并根据确定的读出模式预处理所述捕获光场图像数据，以降低所述捕获光场图像数据的数据大小；以及

处理电路，所述处理电路被配置成处理所述预处理的捕获光场图像数据以产生可视化输出。

49. 根据权利要求 48 所述的装置，其中，所述预处理器被配置成通过以下步骤预处理所述捕获光场图像数据：

根据所述确定的读出模式处理所述捕获光场图像数据的至少一个帧；以及

根据第二个不同的读出模式处理所述捕获光场图像数据的至少一个其它的帧。

50. 一种光场图像捕获装置，包括：

微透镜阵列；

至少一个传感器，所述传感器被配置成捕获代表所述微透镜阵列的输出的光场图像数据，所述光场图像数据包括在所述传感器上形成的圆盘图案，所述至少一个传感器具有彩色滤波阵列 CFA 栅格布局；

预处理器，所述预处理器被配置成访问所述圆盘图案的配置，并确定如何修改所述彩色滤波阵列 CFA 以提高从所述微透镜阵列的输出捕获的色彩信息的质量；

CFA 修改器，所述 CFA 修改器被配置成根据所述确定结果修改所述彩色滤波阵列 CFA；以及

处理电路，所述处理电路被配置成处理所述预处理的光场图像数据以产生可视化输出；

其中，所述圆盘图案和所述彩色滤波阵列 CFA 交互操作以将来自所述微透镜阵列的输出转换成捕获光场图像数据；

并且其中，所述至少一个传感器根据所述圆盘图案和所述修改的彩色滤波阵列 CFA 从所述微透镜阵列的输出捕获光场图像数据。

51. 一种光场图像捕获装置，包括：

微透镜阵列；

至少一个传感器，所述传感器被配置成捕获代表所述微透镜阵列的输出的光场图像数据，所述光场图像数据包括所述至少一个传感器的多个像素中每一个像素的属性；

预处理器，所述预处理器被配置成对于所述至少一个传感器的至少一个像素中的每个像素，基于所述至少一个像素的光坐标，通过调节所述像素的至少一个属性来修改所述像素，以补偿由于所述光场图像捕获装置的其它特征造成的不均匀采样；以及

处理电路，所述处理电路被配置成处理所述预处理的光场图像数据以产生可视化输出。

52. 一种光场图像捕获装置，包括：

孔；

主透镜；

微透镜阵列，所述微透镜阵列具有排列成规则图案的透镜；

至少一个传感器，所述传感器具有排列成规则图案的像素，所述至少一个传感器被配置成捕获代表所述微透镜阵列的输出的光场图像数据，所述微透镜阵列和所述至少一个传感器交互操作以从通过所述孔和所述主透镜的光中捕获光场图像数据；

预处理器，所述预处理器被配置成获取通过所述孔和所述主透镜的光，并将随机变化引入所述微透镜阵列中透镜的规则图案和所述至少一个传感器中的像素的规则图案中的至少一个；

处理电路，所述处理电路被配置成在引入所述随机变化之后，从获取的光中捕获光场图像数据，处理所述预处理的光场图像数据以产生可视化输出。

用于改进的光场捕获和操作的光学系统的优化

[0001] 相关申请交叉引用

[0002] 本申请要求于2012年5月9日申请的名称为“Optimization of Optical Systems for Improved Light Field Capture and Manipulation(律师案号LYT064-PROV)”的美国临时申请序号 61/644,851 的优先权，其公开内容通过引用被全部并入本文中。

[0003] 本申请涉及于 2011 年 2 月 15 日申请的名称为“3D Light Field Cameras,Images and Files,and Methods of Using,Operating,Processing and Viewing Same(律师案号 LYT3006)”的序号 13/027,946 的美国专利申请，其公开内容通过引用被全部并入本文中。

技术领域

[0004] 本发明涉及用于优化光学系统的系统和方法，以用于改进光场图像数据的捕获和操作。

背景技术

[0005] 光场捕获装置（比方说例如光场照相机和摄影机）可以用来捕获及可选地处理光场图像数据。一些光场捕获装置还可以接受用户输入并在用户输入时动作，显示或以其它方式输出图像和／或其它类型的数据。光场捕获装置可以包括用来捕获光场图像数据的各种各样的不同的光学组件，包括传感器（诸如 CCD 或 CMOS 传感器）、微透镜阵列、主透镜和／或透镜阵列。

[0006] 光场捕获装置可以使用任何适当的捕获方法来捕获光场图像数据。这种方法的一个示例包括但不限于如 Ng 等人在“用手持全光捕获装置的光场摄影 (Light field photography with a hand-held plenoptic capture device，Technical Report CSTR 2005-02，Stanford Computer Science)”中描述的在图像传感器（例如，CCD 或 CMOS 传感器）之上使用微透镜阵列。其它示例包括使用多个独立控制的照相机，每个照相机有其自己的透镜和传感器，成像到单个共用传感器上的照相机的阵列，全光透镜和／或这些的任何组合。

[0007] 在许多环境中，光场捕获装置捕获形式为高度调制的 4D 数据的光场图像数据，高度调制的 4D 数据然后可以处理以产生 2D 和／或 3D 输出图像，输出图像可以由用户查看。这种处理的示例可以包括（但不限于）产生重调焦距的图像、视差视图或角度改变的图像、全焦点或扩展景深 (EDOF) 图像、深度图、3D/ 立体图像和其任何组合。

[0008] 光场图像数据的这种处理在计算资源、存储器带宽和／或功率需求方面可能是昂贵的。因此，在许多传统系统中，牺牲图像质量、处理时间、分辨率等等，以便利于光场捕获。因此，一方面，迫使用户在光场图像捕获的灵活性和能力之间权衡，另一方面，在高等级图像质量和分辨率之间权衡。

发明内容

[0009] 根据本发明的各个实施例，光场捕获装置的光学系统被优化，以便改进光场图像

数据的捕获。这种改进可以通过一个或多个尺度测量，包括（但不限于）图像质量、处理效率和产生的图像分辨率。根据各个实施例，多种方法、系统和算法中的任何一个可以应用，以便处理由光场捕获装置捕获的光场图像数据，所述光场捕获装置包括本文中列举的一个或多个光学系统优化。

[0010] 根据各个实施例，光场捕获装置的光学系统被优化以产生更加便宜和／或易于处理的被捕获光场图像数据（静止的和视频）。例如，在至少一个实施例中，光学系统被优化以在使用更加便宜的处理方法时产生改进的质量或分辨率，所述处理方法的计算成本适合各种处理和／或资源约束。因此，光场照相机的光学系统可以被优化以降低大小和／或成本，和／或提高这种光学系统的质量。这些优化在处理能力和／或装置大小可能受限的环境中（比方说例如在诸如智能手机的移动装置的环境中）也许是特别有用的。

[0011] 根据各个实施例，本发明可以单独地或以任何适当组合地包括以下组件或方面中的一个或多个：

[0012] ●修改可以结合微透镜阵列使用以捕获光场图像数据的数字图像传感器的传感器读出能力，使得读出模式针对光场图像数据捕获被裁剪。具体地，通过合并 (binning) 或跳过像素来执行数据大小减小的读出模式被优化，以产生光场图像数据的较小退化。

[0013] ●基于在传感器上形成的光场图像中的圆盘图案，修改传感器的彩色滤波阵列 (CFA) 栅格布局／图案；这可以包括例如如下文更加详细描述的基于其光场坐标逐像素地选择 CFA 色彩。

[0014] ●如在下文更加详细定义的，以像素的光场坐标的函数改变像素属性，诸如曝光时间和像素增益。

[0015] ●抖动微透镜阵列中传感器和／或微透镜上像素的位置。

[0016] ●修改微透镜阵列设计和主透镜设计以及在光学系统内的布置，以产生具有整数个传感器像素的垂直和／或水平间距的圆盘图像，这里，选择整数间距以实现更加便宜、更快速和／或更高质量的处理方法。

[0017] ●修改微透镜阵列和主透镜的设计，以提高光学系统的最大可接受主光线角度 (CRA)。

[0018] ●基于传感器的可用读出模式和／或能力，在数字图像传感器之上定位和／或定向微透镜阵列。

附图说明

[0019] 附图图解说明本发明的几个实施例，与说明书一起用来解释根据实施例的本发明的原理。本领域技术人员会认识到图中图解说明的具体实施例只是示例性的，不想要限制本发明的范围。

[0020] 图 1A 描绘了根据一个实施例的光场图像捕获装置的示例性架构。

[0021] 图 1B 描绘了根据一个实施例的用于执行本发明的光场捕获装置的示例性架构。

[0022] 图 2 描绘了光场图像的一部分。

[0023] 图 3A 描绘了光线通过微透镜传输以照亮数字传感器中的像素。

[0024] 图 3B 描绘了光场捕获装置的布置，其中微透镜阵列被定位成使得投影到数字传感器上的主透镜孔的图像不重叠。

[0025] 图 4 描绘了将 4-D 光场表示降至 2-D 图像的投影和重构的示例。

[0026] 图 5 描绘了根据一个实施例的光场捕获装置的另一示例性架构。

[0027] 图 6 是描绘根据一个实施例的用于降低捕获的光场图像数据的大小的方法的流程图。

[0028] 图 7 描绘了具有中心矩形的光场图像的一部分。

[0029] 图 8 描绘了根据一个实施例的跳过靠近光场圆盘图像之间的边缘或在其上的像素的读出模式的光电二极管的示例性布置。

[0030] 图 9 描绘了根据一个实施例的光场捕获装置的另一示例性架构。

[0031] 图 10 是根据一个实施例的描绘用于修改彩色滤波阵列 (CFA) 以提高从光场捕获的色彩信息的质量的方法的流程图。

[0032] 图 11 描绘了根据一个实施例的光场捕获装置的另一示例性架构。

[0033] 图 12 是根据一个实施例的描绘用于修改像素属性的方法的流程图。

[0034] 图 13 描绘了根据一个实施例的光场捕获装置的另一示例性架构。

[0035] 图 14 是根据一个实施例的描绘用于将抖动引入到光学系统组件中的方法的流程图。

[0036] 图 15 和 16 是根据一个实施例的置换光场数据的示例。

[0037] 图 17A 是光学系统的一个示例。

[0038] 图 17B 是具有圆盘的光场图像的示例。

[0039] 图 17C 是用于光场图像的子采样图案的示例。

[0040] 图 17D 是置换光场图像的子采样部分的示例。

[0041] 图 18A 是光学系统的示例。

[0042] 图 18B 是具有圆盘的光场图像的示例。

[0043] 图 18C 是用于光场图像的子采样图案的示例。

[0044] 图 18D 是置换光场图像的子采样部分的示例。

[0045] 图 19 是根据一个实施例的描绘用于确定并配置用在光场图像捕获装置中的微透镜阵列的方法的流程图。

[0046] 图 20 描绘了两个示例性微透镜阵列的自上而下的视图。

[0047] 图 21 是图 20 中的表面的示例性 3D 曲线图。

[0048] 图 22 描绘了通过倾斜的微透镜的微透镜阵列的示例性 2D 切片。

[0049] 图 23A 和 23B 描绘了倾斜的 MLA 侧壁角的不同优化类型的两个示例。

具体实施方式

[0050] 出于本文中提供的描述目的,使用以下定义 :

[0051] ●捕获 :可以指静态捕获或者视频捕获中的任何一个或者两者。

[0052] ●图像 :像素值或像素的二维阵列,每个像素值或像素规定一个色彩。

[0053] ●光场图像 :包含在传感器上捕获的光场图像数据的呈现的图像。

[0054] ●微透镜 :小的透镜,通常是类似的微透镜阵列中的一个。

[0055] ●彩色滤波阵列 (CFA) :在图像传感器的像素传感器上设置的捕获色彩信息的彩色滤波器的镶嵌 / 马赛克 (mosaic)。

[0056] 光学系统在本文中定义为包括任何适当的光场捕获装置的光学路径的任何或所有组件，包括任何传感器（诸如CCD或CMOS传感器）、微透镜阵列、主透镜和/或透镜阵列。

[0057] 光场捕获装置在本文中定义为能够捕获光场图像数据，可选地处理光场图像数据，可选地接受用户输入并按照用户输入行动以及可选地显示或另外输出图像和/或其它类型的数据的任何装置。光场捕获装置的示例包括（但不限于）光场照相机和摄影机。

[0058] 此外，为便于命名，词语“照相机”在本文中用来指图像捕获装置或其它图像数据获取装置。这种数据获取装置可以是用于获取、记录、测量、估计、确定和/或计算代表场景的数据（包括但不限于二维图像数据、三维图像数据和/或光场图像数据）的任何装置或系统。这种数据获取装置可以包括通过使用本领域众所周知的技术获取代表场景的数据的光学器件、传感器和图像处理电子器件。本领域技术人员会认识到关于本发明可以使用许多类型的数据获取装置，本发明不限于照相机。因此，本文中词语“照相机”的使用想要是示意性的和示例性的，但不应认为是限制本发明的范围。具体地，在本文中任何地方使用此术语应当认为是指用于获取图像数据的任何适当装置。

[0059] 在下面的描述中，描述了用于优化光学系统以用于改进光场捕获和操作的几个技术和方法。本领域技术人员会认识到这些不同的技术和方法可以单独地和/或彼此之间任意适当组合地来执行。

[0060] 架构

[0061] 在至少一个实施例中，本文中描述的系统和方法可以结合由光场捕获装置捕获的光场图像来执行，所述光场捕获装置包括但不限于在Ng等人所著的“Light field photography with a hand-held plenoptic capture device, Technical Report CSTR 2005-02, Stanford Computer Science”中描述的那些装置。现在参照图1A，示出了根据一个实施例描绘用于在光场照相机100中实现本发明的架构的框图。光场照相机100的示例包括（但不限于）光场照相机和摄影机。本领域技术人员会认识到图1A中所示的具体配置只是示例性的，其它架构对于光场照相机100是可行的。本领域技术人员会进一步认识到图1A的配置中所示的几个组件是可选的，可以省略或者被重新配置。

[0062] 如图所示，光场照相机100是光场捕获装置109的一个示例；为了便于命名，这些词语是可互换使用的，不过任何适当的光场捕获装置109可以代替照相机100使用。光场捕获装置109包括光学器件101、微透镜阵列102和图像传感器103（包括多个个别的用于捕获像素的传感器）。光学器件101可以包括例如用于允许可选择数量的光进入到光场照相机100中的孔112和用于将光朝微透镜阵列102聚集的主透镜113。在至少一个实施例中，微透镜阵列102可以设置和/或包括于照相机100的光学路径中（在主透镜113和传感器103之间），以便使得通过传感器103获取、捕获、采样、记录和/或获得光场图像数据。暂时参照图1B，示出了根据一个实施例的用于实现本发明的光场照相机100的架构的示例。该图不是按比例绘制的。图1B以概念形式示出了孔112、主透镜113、微透镜阵列102和（若干）传感器103之间的关系，这些组件相互作用以捕获主体117的光场图像数据。

[0063] 再次参照图1A，来自（若干）传感器103的光场图像数据可以被处理电路104处理，在（若干）输出装置116上呈现为输出。在至少一个实施例中，在（若干）输出装置116上呈现的输出可以是由处理电路104产生的光场图像数据的2D图像或投影。

[0064] 在至少一个实施例中，光场照相机100还可以包括控制电路110，以便利获取、采

样、记录和 / 或获取光场图像数据。例如，控制电路 110 可以管理和 / 或控制（自动地或者响应于用户输入）获取时间、获取速率、采样、捕获、记录和 / 或获得光场图像数据。

[0065] 在至少一个实施例中，捕获的光场图像数据提供至处理电路 104。处理电路 104 可以设置在或集成到光场捕获装置 109 中（如图 1A 中所示），或者可以是光场捕获装置 109 外部的单独组件。此单独的组件可以相对于光场捕获装置 109 在本地或在远处。任何适当的有线或无线协议可以用来将光场图像数据发射到电路 104；例如，装置 109 可以通过互联网、蜂窝数据网络、WiFi 网络、蓝牙通信协议和 / 或其它任何适当手段发射光场图像数据 / 或其它数据。

[0066] 通常，处理电路 104 对从（若干）光场传感器 103 接收的光场图像数据进行操作，产生任何输出，比方说例如静止图像、2D 视频流等等。在各个实施例中，处理电路 104 可以使用由光场图像数据（包括但不限于在下文和交叉引用的相关申请中描述的那些）产生静止图像、2D 图像等等的任何适当方法。

[0067] 在至少一个实施例中，光场照相机 100 还可以包括用户界面 105，用户界面 105 允许用户提供用户输入以控制照相机 100 的操作以捕获、获取、存储和 / 或处理图像数据。在至少一个实施例中，还可以使用用户偏好，如由用户在偏好屏幕上指定的，或者基于默认值提供的。用户输入可以通过任何适当的（若干）用户输入装置 111（诸如触摸屏、按钮、键盘、指针装置和 / 或等等）提供给用户界面 105。由此，在（若干）输入装置 111 上接收的输入可以用来控制和 / 或配置处理电路 104 和控制电路 110 中的任何一个。

[0068] 在至少一个实施例中，照相机 100 包括一个或多个存储装置 114，诸如用于存储来自（若干）光场传感器（并且可能被处理电路 104 处理过）的图像数据输出的存储器。存储器可以包括外部和 / 或内部存储器。在至少一个实施例中，存储器可以在与照相机 100 单独的装置和 / 或位置上提供。

[0069] 例如，照相机 100 可以存储如由传感器 103 输出的原始光场图像数据，和 / 或其表示，诸如压缩的图像数据文件。此外，如在 2010 年 2 月 10 日申请的名称为“Light field Camera Image, File and Configuration Data, and Method of Using, Storing and Communicating Same,”（律师案号为 LYT3003）的相关美国专利申请序号 12/703,367 中描述的，存储器还可以存储代表装置 109 的特征、参数和 / 或配置（共同称作“配置数据”）的数据。

[0070] 综述

[0071] 光场图像通常包括照相机 100 的孔 112 的多个投影（可以是圆形的或者其它形状的），每个投影取自照相机 100 的焦平面上的不同的有利点。可以在传感器 103 上捕获光场图像。微透镜阵列 102 插入到主透镜 113 和传感器 103 之间，引起孔 112 的图像形成于传感器 103 上，阵列 102 中的每个微透镜将主透镜孔 112 的微小图像投影到传感器 103 上。这些孔形状的投影在本文中称作圆盘 (disk)，不过他们的形状不必需是圆形的。

[0072] 光场图像包括描述入射到照相机 100（或其它捕获装置）的焦平面上的光线的四维信息。两个空间维度（本文中称作 x 和 y）由圆盘本身表示。例如，设置成宽 400 高 300 的笛卡尔图案的具有 120,000 个圆盘的光场图像的空间分辨率是 400×300。两个角维度（本文中称作 u 和 v）表示为单个圆盘中的像素。例如，设置成 10×10 笛卡尔图案的每个圆盘内具有 100 个像素的光场图像的角分辨率是 10×10。光场图像具有 4-D(x,y,u,v) 分辨

率(400,300,10,10)。现在参照图2,示出了此光场图像200的2圆盘×2圆盘部分的示例;包括圆盘201和各像素203的描述;出于图示目的,每个圆盘201的宽为10个像素203。

[0073] 相应地,在光场捕获装置109的传感器103上形成的图像包括微小图像的集合,称作"圆盘图像"(不过他们的形状不必要是圆形的),其对4D光场图像数据的集合进行编码。传感器103上的每个像素203可以解释为对应于特定的4D光场坐标,其中,两个维度规定其在传感器上的空间位置,两个维度规定入射到该像素203的光的角度或方向信息。2D方向信息由像素203在其为成员的圆盘图像内的2D位置来编码。

[0074] 在光场照相机内的光场中的许多光线对单个像素203的照亮有贡献。现在参照图3A,示出了光线202(包括代表性光线202A、202D)通过阵列102的微透镜201B传输以照亮传感器103中的传感器像素203A、203B的一个示例。

[0075] 在图3A的示例中,实心光线202A、202B、202C照亮传感器像素203A,而虚线光线202D、202E、202F照亮传感器像素203B。在每个传感器像素203的值由照亮它的所有光线202的辐射度的总和确定。出于示意和描述目的,然而,可以用每个传感器像素203来识别单个几何光线202。该光线202可以选择为代表照亮该传感器像素203的所有光线202,因此在本文中称作代表光线202。此代表光线202可以选择为通过特定的微透镜201的中心并照亮特定的传感器像素203的中心的那些光线。在图3A的示例中,光线202A和202D描绘为代表光线;两个光线202A和202D都穿过微透镜201B的中心,光线202A代表照亮传感器像素203A的所有光线202,光线202D代表照亮传感器像素203B的所有光线202。

[0076] 在传感器像素203和他们的代表光线202之间可以存在一对一的关系。此关系可以通过设置主透镜孔112相对于微透镜阵列102的(明显)大小和位置来加强,使得孔112投影到传感器103上的图像不重叠。现在参照图3B,示出了诸如照相机100的光场捕获装置的布置的示例,其中,微透镜阵列102被定位成使得主透镜孔112投影到传感器103上的图像不重叠。图3B中描绘的光线202是代表光线202,原因是他们全部通过微透镜201之一的中心到达光场传感器803的像素203的中心。

[0077] 在至少一个实施例中,4-D光场呈现可以通过投影和重构的过程降低为2-D图像。现在参照图4,示出了这种过程的一个示例。可以引入虚拟投影面401,计算每个代表光线202与投影面401的交叉点。投影面401可以是平面的或不是平面的。如果是平面的,则它可以平行于微透镜阵列102和传感器103,或者它可以不平行。通常,投影面401可以相对于微透镜阵列102和传感器103定位在任何任意的方向。每个代表光线202的色彩可以采用等于其相应的像素203的色彩。在至少一个实施例中,传感器103的像素203可以包括排列成规则图案(诸如Bayer图案)的滤波器,并转换成全色像素。这种转换可以在投影之前发生,使得投影光线202可以无偏差地重构。替代性地,可以为每个色彩信道执行单独的重构。

[0078] 投影面401上的图像像素402的色彩可以通过对与图像像素402的域内的投影面401相交的代表光线202的色彩求和来计算。域可以在图像像素402的范围之内,或者可以扩展到图像像素402的范围之外。求和可以被加权,使得不同的代表光线202将不同的部分贡献到求和中。光线权重可以被赋值,例如以光线202和投影面401之间的相交位置相对于特定的像素402的中心的函数。可以使用任何适当的加权算法,包括例如双线性加权算法、双三次加权算法和/或高斯加权算法。

[0079] 在投影到重新聚集的 2-D 图像的过程中，代表光线 202 与虚拟投影面 401 相交，虚拟投影面 401 与微透镜阵列 102 平行但有位移。如果虚拟投影面 401 在微透镜阵列 102 前面（更靠近场景），则重构的 2-D 图像聚集到在光场照相机 100 的最佳聚集场景平面之前的虚拟投影面 401。（它离光场照相机 100 更远）。类似地，如果虚拟投影面 401 在微透镜阵列 102 后面（离场景较远），则重构的 2-D 图像聚集到在光场照相机 100 的最佳聚焦场景平面后面的虚拟投影面 401 上。景深与虚拟投影面 401 的图像深度对应的场景中的物体基本上精确聚焦；场景中的其它物体有模糊地投影，此模糊程度随着与景深的位移而增加。

[0080] 深度图是图像侧点（主透镜 113 的图像侧上的点）的集合，每个点对应于场景中的可见点。场景中的点在其发射的光直接地或者通过从高度反射面反射从而到达主透镜 113 的前面的节点时是可见的。此对应使得从场景点发射的光是主透镜 113 在相应的图像侧点的最佳聚焦。

[0081] 可以在笛卡尔坐标中规定图像侧点在深度图中的位置，x 和 y 表示投影到光场传感器 103 上的位置（在沿着主透镜 113 的光学轴线朝场景观看时，x 朝右为正，y 向上为正），深度 d 表示与微透镜阵列 102 的表面的垂直距离（朝向场景为正，离开场景为负）。x 和 y 的单位可以是像素 203- 传感器 103 的像素间距。d 的单位可以是拉姆达，其中，一拉姆达的距离对应于这样一个距离，沿着该距离来自任何场景点的光锥将其直径改变一个等于微透镜阵列 102 的间距的值（微透镜阵列 102 的间距是相邻的微透镜 201 的中心之间的平均距离）。

[0082] 因此，对于对主透镜 113 直接可见的场景侧的点，在光学焦点的平面上的景深的点对应于（微透镜）表面的图像深度。距离光场照相机 100 比距离最佳焦点的平面更远的景深的点对应于图像深度比最佳焦点的平面更靠近主透镜 113 的点。因此，距离光场照相机 100 比距离最佳焦点的平面更远的景深的点具有正的深度值。相比最佳焦点的平面更靠近照相机 100 的景深的点对应于图像深度距离主透镜 113 比最佳焦点的平面更远的点。因此，相比最佳焦点的平面更靠近照相机 100 的景深的点具有负的深度值。

[0083] 根据本发明的各个实施例，可以进行任何数目的变形，以便优化光场捕获装置 109 的光学系统，从而改善捕获的光场图像数据。这种变形的示例在本文中描述。本领域技术人员会认识到这些变形可以单独地或者以任何适当的组合来应用。

[0084] 传感器读出变形

[0085] 根据至少一个实施例，数字图像传感器（例如，光场传感器 103）的传感器读出能力被修改。传感器读出变形可以与微透镜阵列（例如微透镜阵列 102）结合使用，以捕获光场图像数据，使得传感器的读出模式被裁减以用于光场图像数据捕获。读出模式被优化以产生较不退化的光场图像数据。许多个不同的读出变形在本文中列出；然而，此列表是示例性的。这些变形中的任何一些或全部可以被单独地或者以任何适当组合来应用。

[0086] 现在参照图 5，示出了根据一个实施例的光场捕获装置 109 的另一个示例性架构。如图 5 中描绘，光场传感器 103 包括缓存器 502 和预处理 503。预处理 503 进一步包括滤波器 504 和数据精简 506。通常，光场传感器 103 可以从微透镜阵列 102 的输出捕获光场图像数据 501（例如如关于图 1A 到 4 描述的）。光场图像数据 501 中的一些或者全部可以在缓存器 502 中缓存和 / 或发送到预处理 503。

[0087] 预处理 503 可以根据读出模式 507 处理光场图像数据 501，以没有任何可察觉的退

化地来降低捕获的光场图像数据的数据大小。预处理 503 可以将预处理的光场图像数据输出到处理电路 104 以用于进一步的处理，例如产生 2D 图像。

[0088] 在至少一个实施例中，滤波器 504 过滤光场图像数据 501 以降低光场图像数据 501 的大小。滤波的光场图像数据可以存储在缓存器 502 中。数据精简 506 可以从缓存器 502 中访问光场图像数据 501 和／或可以访问经过滤波的光场图像数据。数据精简 506 可以实现一个或多个机制以降低光场图像数据的大小。在一些实施例中，数据精简 506 使用以下当中的一个或多个：跳过像素 203、合并像素 203、子采样像素 203、重采样像素 203、逐像素操作、逐像素值、位掩码、位掩码瓦片 (bitmask tile)、加权图像瓦片、位深变形、像素最大化、查询表、多道 (muli-pass) 读出、光场感知处理以及用隔行扫描的传感器来降低光场数据的大小。

[0089] 现在参照图 6，示出了描绘用于降低捕获的光场图像数据的大小的方法的流程图。图 6 的方法将参照图 5 中的组件和数据进行描述。

[0090] 在至少一个实施例中，一个或多个光场传感器 103 从微透镜阵列 102 的输出捕获 601 光场图像数据 501。捕获的光场图像数据 501 根据特定的读出模式在一个或多个光场传感器 103 上被预处理 602，以降低捕获的光场图像数据的数据大小。例如，预处理 503 可以根据读出模式 507 处理光场图像数据 501 以降低光场图像数据 501 的大小。预处理的捕获光场图像数据然后发送 603 到处理电路 104。

[0091] 预滤波传感器图像数据

[0092] 在至少一个实施例中，图像数据 501 在被传感器 103 读出之前被滤波。在使用子采样、合并或重采样的读出模式时，滤波可以在子采样、合并或重采样之前进行。例如，一个读出模式可以涉及跳过列，水平滤波器可以在此跳过过程之前施加到传感器数据。

[0093] 通常，滤波可以是水平的、垂直的或者二维的。二维滤波器可以是或者可以不是单独的。滤波可以实现为用提供的掩码直接卷积图像数据。在至少一个实施例中，滤波可以施加到同一色彩的像素 203 中。例如，在至少一个实施例中，相同色彩的滤波可以用于图像传感器，其中，不同的像素 203 代表不同的色彩（例如，使用彩色滤波阵列 (CFA) 的传感器，诸如 Bayer 传感器）。替代性地，这种图像的滤波可以实现为考虑多个彩色的像素 203，例如在去马赛克／解镶嵌 (demosaic) 算法中。

[0094] 滤波可以使用传感器本身上的小容量的存储器来实现，以在从像素 203 的阵列读出行时缓存行；这种缓存行可以根据已知的技术来执行。滤波操作可以施加到这些缓存行，在垂直或二维滤波器的情况下，缓存行的数目可能需要至少与垂直维度上滤波器的抽头的数目一样大。

[0095] 一旦数据在本地缓存器（诸如缓存器 502）中滤波，可以施加随后的操作，包括（但不限于）子采样、合并或者重采样，之后数据最终从传感器 103 输出。

[0096] 此传感器性能的一个优点是预滤波（可能是高度地）调制的光场图像数据，再子采样，例如传感器图像被子采样并调整为适合用于照相机上的实时观看操作的 LCD 屏幕。子采样以及然后降低高度调制的光场图像数据的规模而没有足够大的预滤波操作可能造成最终图像中由于混叠图案造成的不受欢迎的制品。

[0097] 滤波可以在空间上变化，或者可以在整个光场图像上是均匀的。在空间变化的滤波器情况下，变化可以是被滤波的像素 203 的光场坐标的函数，这种方法可以用来在光场

图像的高度调制的区域中施加更大的滤波（因此有更大量的像素聚合）。

[0098] 基于其光场坐标跳过像素

[0099] 在至少一个实施例中，传感器读出模式可以基于其光场坐标跳过像素 203，而不是使用一些（传感器－表面）均匀的和／或光场遗忘方法跳过像素 203，诸如每隔一行或一列跳过。

[0100] 如上文描述的，通过在传感器 103 上设置的微透镜阵列 102 捕获的光场图像可以包括大量的圆盘 201。更靠近圆盘 201 的中心的像素 203 倾向于被照得更亮，具有比更靠近圆盘 201 的边界的像素 203 更高的信噪比 (SNR)。在这种光场图像中，4D 坐标空间的二个方向维度指像素 203 在圆盘 201 中的位置，可以执行以这些方向维度的函数选择要跳过的像素 203，以确保只有更靠近圆盘 201 的中心的像素 203 从传感器 103 中读出。

[0101] 例如，如图 7 描绘的，给定光场传感器 103 和微透镜阵列 102 的配置，使得每个圆盘图像 201 的直径大约为 10 个传感器像素 203，可以为每个圆盘 201 定义 8x8 中心矩形 731 的像素 203，使得矩形 731 几乎被完全地包含于圆盘 201 中。传感器 103 可以包括一些容量的本地存储器，以在从传感器 103 读出数据之前缓存可以用来将 8x8 矩形 731 包装成连续的块的多行像素数据。

[0102] 在至少一个实施例中，其中，传感器像素 203 是由于在彩色滤波阵列 (CFA) 下的单一色彩，中心矩形 731 可以选择为包装在一起，使得在包装之后，所产生的图像是在产生图像的范围上 CFA 图案的合法示例。在 (R，GR，GB，B)Bayer 传感器情况下，矩形 731 可以选择为使得（例如）相同色彩的像素（例如 R）在每 8x8 块的左上方。

[0103] 要跳过的像素 203 和／或要包装到一起的像素区的位置可以以任何种可行的方式规定。一个示例是提供每个圆盘 201 的中心的传感器坐标。此数据还可以存储在传感器中专用于此目的的小的本地存储器（未显示）中。

[0104] 逐像素读出操作

[0105] 在各种实施例中，本发明的系统和方法提供完全可配置的并且可以以逐像素方式规定或配置的传感器读出图案。

[0106] 在至少一个实施例中，可以提供位掩码，位掩码对于每个像素 203 规定其是被跳过还是不被跳过，不跳过的像素 203 可以在数据中被包装在一起，从传感器 103 输出。这种位掩码可以编程到传感器 103 的本地存储器中，或者可以提供于 DRAM 或传感器 103 可以访问的其它存储器中。进一步，多个位掩码可以编程到传感器中以允许快速切换读出图案。

[0107] 在另一实施例中，可以提供一个或多个位掩码瓦片，这些瓦片可以在不同的传感器区域上重复使用以规定跳过哪些像素 203。

[0108] 在进一步的实施例中，不是位掩码规定要被读取或跳过的像素 203，可以提供加权图像或一个或多个加权图像瓦片。如上文描述的位掩码方法一样，读出图案可以基于逐像素基础规定。然而，在这种方法中，不是每个像素相应的位掩码布尔表项规定是否跳过像素 203，可以规定逐像素加权因数（即乘积因子），其中，这些权重与被读出的像素值相乘。而且，在读出过程中任何其它的像素 203 的跳过、合并、重采样或聚合可以与这种逐像素加权操作结合执行。

[0109] 在另一实施例中，除了或代替提供逐像素加权数据之外，可以提供逐像素偏移值，其中，读出像素值是根据以下公式计算的，这里，计算的像素值钳制到合法像素值范围，如

下所示：

[0110] PixelValue' = CLAMP(PerPixelOffset+PerPixelWeight*PixelValue,0,MAX)

[0111] 由逐像素跳过规定实现的（许多）可行的读出图案中的一个是随机或伪随机图案；例如，在重复瓦片图案中，被跳过的像素 203 具有看起来似乎是随机的位置集合。

[0112] 在至少一个实施例中，本文中描述的算术运算可以使用标准定点运算来实现。

[0113] 读出位深变形

[0114] 在至少一个实施例中，数字图像传感器 103 的读出位深可以修改为利用在光场处理算法中执行的大量的像素聚合。通过利用适当数目的位来对每个原始像素 203 编码，并定义由原始线性值到编码值的映射函数，可以降低来自传感器的读出数据速率（用字节 / 秒来测量）以获得给定数目的像素 / 秒。任何适当的编码可以用来利用像素 203 的光场坐标和 / 或传感器 103 上的光场圆盘图案。

[0115] 一个示例性编码输出每个像素具有可变位数的原始数据，这里，像素 203 在传感器暴露期间具有"更好"或"更多"的光捕获，这可以具有用较高位深编码的相应的值。对于在微透镜阵列 102 下面的传感器 103 上捕获的光场图像（例如，根据上文描述的架构），所产生的圆盘图像在更靠近圆盘 201 的中心具有更多的光捕获的像素 203；因此，更多的位可以用来编码圆盘 - 中心像素相对圆盘 - 边缘像素。

[0116] 另一示例性编码可以使用像素特定的最大值，像素值被钳制到该最大值。例如，在许多情况下，在光场图像中靠近圆盘 201 的中心的像素比靠近圆盘 201 的边缘的像素亮很多，除了在过饱和的情况下。圆盘 - 边缘像素可以钳制到比圆盘 - 中心像素可以保持的值更小的最大值。

[0117] 另一实施例可以使用可变位深和可变像素最大值方法的组合。这种读出图案的一个示例可以使用每个像素 12 位 (bpp) 来对圆盘 - 中心像素 203 的范围 [0,4095] 中的值编码，使用 6bpp 来对圆盘 - 边缘像素 203 的范围 [0,1023] 中的值编码（这里，64 个可行的编码值在 1024 个像素值的范围中均匀间隔开）。

[0118] 在另一示例性实施例中，一个或多个查询表可以用来将传感器值映射为编码值，其中，查询表可以由用户编程，选择哪个查询表应用到任何特定像素 203 是根据其光场坐标确定的，例如根据其相对于其圆盘 201 的中心的位置确定的。不同的查询表甚至查询表内的不同的表项可以是变化位长的或者不是变化位长的，从传感器读出的像素 203 的顺序可以具有包装在一起的任何大小可变的像素值。

[0119] 与预滤波的实施例一样，在至少一个实施例中，这种像素位深变形可以通过逻辑实现，所述逻辑作用于像素 203 的小数目的缓存行上，之后在传感器界面上读出。

[0120] 渐进式多道读出

[0121] 在至少一个实施例中，传感器图像数据可以以多次读出，其中，每次读取在传感器 103 上间隔开并与在其它次读出的行隔行的行的集合。这种读出方法通过后续的数据处理实现了诸如分解照相机运动与物体运动以及 HDR 成像的特征。

[0122] 读出次数以及每次读取的相应行的集合可以是硬连线的或者是可编程的。

[0123] 在读出过程中执行光场感知处理

[0124] 在至少一个实施例中，可以在图像传感器 103 上执行光场感知处理，使得从传感器 103 读出的数据已经以某种方式处理过。光场感知处理操作的示例包括（但不限于）：

[0125] ●将光场图像数据从“圆盘阵列”格式置换成“子孔径图像阵列”格式；

[0126] ●将4D数据转换成2D数据，例如通过重新聚焦，通过产生全聚焦或扩展景深(EDOF)图像，或者通过产生具有视差或视角转变的图像。

[0127] 不同帧上的不同的读出图案

[0128] 在至少一个实施例中，对于不同的帧特别是视频帧可以提供不同的读出模式。通常，本文中描述的任何读出模式的实施例可以对不同的帧变化。

[0129] CCD传感器上的光场图像读出

[0130] 在至少一个实施例中，只要微透镜阵列几何结构中的一些或全部在图像传感器103制造时是是已知的或者确定的，则本文中描述的至少一些图像读出模式可以使用电荷耦合装置(CCD)图像传感器103来实现。与CMOS图像传感器不同，CCD通常没有单独可寻址的像素203，依赖于用于读出的电荷转移。这对在这种图像传感器103上执行任意的读出模式提出挑战，原因是像素读出的本地次序和图案在设计半导体器件本身时是固定的。

[0131] 用于实现以依赖于具体的微透镜阵列几何形状的特定次序或方式读出像素203或另外更好地适于微透镜成像的全分辨率或分辨率降低的读出模式的一种方法是使用具有隔行扫描的行间、帧行间转移或任何其它类型的CCD图像传感器103。图像传感器103构造有逐像素微透镜、光电二极管、传输门、垂直电荷耦合装置(VCCD)和/或根据光场微透镜阵列102的几何形状排列的其它定制图像传感器部分，以便允许实现本文中描述的（一种或若干）读出模式。在其它方面，图像传感器103可以以适于CCD图像传感器的任何方式构造。

[0132] 现在参照图8，示出了根据一个实施例的跳过靠近光场圆盘图像之间的边缘或者在其上的像素203的读出模式的光电二极管701的示例性布置。图8描绘了具有六角形光场微透镜阵列图案703的8-场隔行读出图像传感器的光电二极管701和VCCD 702的逻辑配置。为了简洁，省略了传输门（或者金属层的任何其它部分）、孔、彩色滤波阵列和逐像素微透镜。图不是按比例绘制的。在此示例中，读出场1、2、3和4产生只覆盖处于微透镜阵列图像的中心的像素203的半分辨率模式。

[0133] 改变图像传感器的彩色滤波阵列图案

[0134] 在至少一个实施例中，给定图像传感器上的微透镜阵列，例如，传感器103上的微透镜阵列102，施加到图像传感器103的彩色滤波阵列(CFA)图案可以被修改以提高从光场捕获的色彩信息的质量。为每个像素203选择的色彩可以（或者也可以不）是其光场坐标的函数。

[0135] 现在参照图9，示出了根据一个实施例的光场捕获装置109的另一示例性架构。如图9中描绘的，光场传感器103包括圆盘图案901（例如规定在传感器103上形成的捕获光场图像数据中圆盘102的布置）、彩色滤波阵列(CFA)栅格布局902和CFA调节器903。根据本发明的技术，CFA调节器903可以基于圆盘图案901修改CFA栅格布局902。

[0136] 现在参照图10，示出了根据一个实施例的描述用于修改彩色滤波阵列(CFA)以提高从光场捕获的色彩信息的质量的方法的流程图。出于图示目的，将参照图9中的组件和数据描述图10的方法。

[0137] 在至少一个实施例中，CFA调节器903访问1001圆盘图案901的配置。CFA调节器903然后确定1002如何修改彩色滤波阵列(CFA)以提高从微透镜阵列102的输出捕获

的色彩信息的质量。CFA 调节器 903 然后根据其确定结果修改 1003CFA 栅格布局 902。然后,光场传感器 103 根据圆盘图案 901 和修改后 CFA 栅格布局 902 从微透镜阵列 102 的输出捕获 1004 光场图像数据。光场传感器 103 然后将捕获的光场图像数据发送 1005 到处理电路 104。

[0138] 在各个实施例中,可以以各种方式修改彩色滤波阵列,包括但不限于:不向一些像素 203 施加彩色滤波,改变彩色滤波通带和/或随机化彩色滤波阵列图案。

[0139] 在各个实施例中,CFA 图案变形包括但不限于以下:

[0140] 对某些像素不施加彩色滤波

[0141] 接收由微透镜阵列 102 强调制的光的像素 203 可以不经过任何彩色滤波以提高在相同的曝光时间中由像素 203 捕获的光子的量。在稍后的处理阶段,不经过彩色滤波的像素 203 可以用作照明信号源(单色图像),其色度分量可以与附近的像素 203 内插。

[0142] 改变彩色滤波通带

[0143] 接收较少光的像素 203 可以具有有较宽通带的彩色滤波器(负的),而接收较多光的像素 203 可以具有较窄的通带。例如,朝微透镜图像的边缘的像素 203 可以具有青色/品红/黄色的彩色滤波器图案,而朝微透镜图像的中心的像素 203 可以具有红色/绿色/蓝色的彩色滤波器图案。这允许边缘像素 203 在其彩色滤波器中衰减较小的信号,提高到达光传感器的光子的数目。

[0144] 随机化彩色滤波器阵列图案

[0145] 为了减少可能由彩色滤波器阵列图案的规则性造成的问题,可以随机化彩色滤波器阵列的布置。可以记录在每个像素 203 上的彩色滤波器的类型,并使其对处理软件/硬件已知。

[0146] 改变图像传感器的像素属性

[0147] 假定微透镜阵列 102 位于图像传感器 103 上,则由于取决于传感器角度响应的各种因数以及微透镜阵列 102 和/或主透镜 113 的光学特征,基于像素在每个微透镜 201 下的位置可以由不同的像素 203 捕获不同量的光。在至少一个实施例中,可以基于每个像素 203 的光场坐标调节个别像素的属性,以补偿这些效应并产生更加均匀(或者有意不均匀)的采样。

[0148] 现在参照图 11,示出了根据一个实施例的光场捕获装置 109 的另一示例性架构。如图 11 中描绘的,光场传感器 103 包括像素调节器 1106。通常,像素调节器 1106 可以访问像素 203 的光场坐标,基于像素 203 的光场坐标对像素 203 的属性进行相应改进。

[0149] 现在参照图 12,示出了根据一个实施例的描绘用于修改像素属性的方法的流程图。将参照图 11 中的组件和数据描述图 12 的方法。

[0150] 传感器 103 从微透镜阵列 102 的输出捕获 1201 光场图像数据,光场图像数据包括每个像素 203 的属性。然后,对于光场图像数据中包括的一个或多个像素值中的每个像素值,像素调节器 1106 访问像素 203 的坐标 1103,通过调节像素 203 的一个或多个属性来修改 1202 像素 203,以补偿由于光场捕获装置 109 的其它特征造成的不均匀采样。例如,像素调节器 1106 可以通过基于坐标 1103 调节属性 1104 来修改像素 203。捕获的光场图像数据(包括修改后的一个或多个像素 203)然后发送 1203 到处理电路 104。

[0151] 可以被调节的像素属性的示例包括但不限于:

[0152] ●每个像素 203 特有的曝光时间。

[0153] ●在像素调节器、列放大器、行放大器和 / 或其它任何模拟或数字放大级上给信号施加的任何种类的增益。

[0154] ●在光电二极管、任何放大器、数字 / 模拟转换器 (DAC) 和 / 或其它任何处理级上给信号施加的任何各类偏置和 / 或偏移。

[0155] 这些属性可以在每个像素变化和 / 或在每组像素 203 上变化。例如，在至少一个实施例中，这些可以是固定数目的不同参数的集合，每个像素 203 可以根据这些参数集合中的一个配置。

[0156] 用于调节这些属性的方法包括但不限于 :

[0157] ●任何各类的半导体制造后的局部修整。

[0158] ●实现 (例如以硬件) 在图像曝光之前作为数字或模拟信号提供的可设置的每个像素或每个像素组的曝光规模或偏移、信号增益、信号偏置或信号偏移。

[0159] ●实现 (例如以硬件) 在制造时存储在半导体熔丝中的可设置的每个像素或每个像素组的曝光规模或偏移、信号增益、信号偏置或信号偏移。

[0160] ●实现 (例如以硬件) 在以数字或模拟信号的图像读出期间同步提供的每个像素或每个像素组的信号增益、信号偏置或信号偏移。

[0161] 移动 / 抖动像素和 / 或微透镜

[0162] 如上文描述的，在至少一个实施例中，传感器 103 上的像素 203 可以排列成规则图案，诸如正方形图案。类似地，微透镜阵列 102 上的透镜 201 也可以排列成规则图案，诸如正方形图案或六角形图案。然而，扰乱这些规则图案之一或两者可能是有优点，使得引入位置的小的随机变化。这些位置的随机变化在本文中称作“抖动”;抖动的引入在本文中称作“抖动”。在计算机图形领域众所周知的是抖动采样位置将混叠转换成噪声。例如，参见 Cook，Robert L. 所著的 Stochastic Sampling in Computer Graphics，ACM Trans. Graph. 5，1(1986)。因为微透镜 201 和像素 203 的位置基本上确定进入照相机 100 的光场的采样图案，这些优点还可以归于光场采样。相关优点是还可以降低在光场的重新投影的采样图案中的规则性。也可以有另外的优点。

[0163] 现在参照图 13，示出了根据一个实施例的光场捕获装置 109 的另一示例性架构。如图 13 中描绘的，光场图像数据 109 包括抖动模块 1301。抖动模块 1301 被配置成将抖动引入到微透镜阵列 102 和 / 或 (若干) 光场传感器 103 中。

[0164] 现在参照图 14，示出了根据一个实施例的描绘用于将抖动引入到光学系统组件中的方法的流程图。将参照图 13 中的组件和数据描述图 14 的方法。

[0165] 在至少一个实施例中，选取已经通过孔 112 和主透镜 113 的光 1303。如图 13 中描绘的，光 1302 传输进入到照相机 100 中，光 1303 从光学器件 101 中出来。抖动模块 1301 例如通过改变微透镜阵列 102 中的透镜 201 和 / 或一个或多个光场传感器 103 中的像素 203 的位置来引入 1402 随机变化。

[0166] 在引入随机变化之后，例如通过微透镜阵列 102 和 (若干) 光场传感器 103 从选取的光 1303 捕获 1403 光场图像数据 1304。捕获的光场图像数据 1304 发送 1404 到处理电路 104。

[0167] 抖动图案在任何规模上可以是随机的。在一种极限情况下，图案可以延伸整个范

围，即在整个微透镜阵列 102 或整个传感器 103 上。在另一种极限情况下，图案可以是在微透镜阵列 102 或传感器 103 上重复的小的瓦片。在这些极限情况之间存在较大瓦片和较大瓦片的随机图案。瓦片的动机可以是降低处理成本，原因是正确地解释采样位置所需的表更小。抖动采样的大部分优点可以随合理小的瓦片而增加。例如，可以为每个圆盘中的 10 个像素 203 执行相同图案的像素抖动。

[0168] 在至少一个实施例中，传感器 103 上的像素 203 可以具有其真实的抖动位置。替代性地，像素 203 可以设置在规则栅格上，但通过对设置在每个像素位置上的透镜进行调节来使其看起来被抖动（这些透镜旨在将撞击到传感器 103 上的光朝电子像素结构的光敏部分引导）。只调节传感器 103 的表面上的光学器件，而不是对传感器 103 本身进行变化可能是花费较少的，可以用较大的瓦片来实现。像素抖动可以与像素大小的变化结合执行，像素抖动还可以直接地在传感器 103 中引入，或者通过对传感器 103 的表面上的光学器件进行改动来引入。

[0169] 在至少一个实施例中，抖动微透镜位置和 / 或像素位置是以这样一种方式执行的，这种方式确保任何两个透镜位置都不会更靠近圆盘的直径。因此，避免圆盘的重叠，否则这可能引起像素值不被正确地解释。接近度的约束可以用随机抖动来满足。替代性地，以微透镜的位置的附加约束来满足接近度约束可能更加有效。例如，退火算法可以允许近随机抖动和最小距离约束被同时地执行。具体地，抖动可以在整个瓦片中随机引入，然后在违反最小距离约束的情况下，采样可以是重新抖动的；此过程可以重复直到满足约束。

[0170] 整数间距的圆盘图像设计

[0171] 在至少一个实施例中，可以对微透镜阵列 102 和主透镜 113 的设计及在光学系统 101 中的设置进行改进，以便产生具有整数个传感器像素 203 的垂直和 / 或水平间距的圆盘图像，这里，整数间距选择为能够实现更加便宜、更快速和 / 或更高质量的处理方法。这些方法包括（但不限于）下文描述的那些方法。

[0172] 传感器 103 上的圆盘图像的间距由微透镜阵列 102 的间距、其与传感器 103 的间隔以及与主透镜 113 出射光瞳的距离控制。适当地选择这些参数以及还确保微透镜阵列 102 相对于传感器 103 不进行空间旋转，这允许光场圆盘图像被捕获，其中，在水平和垂直方向之一或两者的圆盘间距是整数。

[0173] 除了圆盘间距是整数值之外，可以施加的另一种设计约束是确保微透镜阵列 102 适当地排列在传感器 103 之上，使得微透镜阵列 102 中的每一行微透镜 201 平行于传感器像素 203 的行。除了平版印刷制造方法之外，使用晶圆至晶圆的制造技术是可行的。

[0174] 例如，再次参照图 1A、1B、2 和 7，主透镜 113 和微透镜阵列 102 可以设置成在（若干）传感器 103 上产生具有整数个传感器像素 203 的垂直和 / 或水平间距的圆盘图像 201（或中心矩形 601）。替代性地或者相结合，微透镜阵列 102 和（若干）传感器 103 之间的间隔可以选择为便利（若干）传感器 103 上的整数个传感器像素 203 的垂直和 / 或水平间距。替代性地或者相结合，微透镜阵列 112 可以被配置成确保它相对于（若干）传感器 103 不进行空间旋转。替代性地或者相结合，微透镜阵列 102 可以被配置成确保它在（若干）传感器 103 上适当地对齐，便利微透镜阵列 102 中的每行微透镜 201 平行于传感器 103 中的一行传感器像素 203。

[0175] 在至少一个实施例中，主透镜 113 是移动的主透镜。主透镜 113 可以是确保在主

透镜 113 移动时（例如它缩放时），（若干）传感器 103 上的圆盘图像间距保持恒定和为整数的设计。例如，对于所有的焦距，主透镜 113 可以具有与（若干）光场传感器 103 的传感器表面充分远（相对于传感器尺寸）的出射光瞳。

[0176] 置换成子孔径图像的阵列

[0177] 在至少一个实施例中，光学系统被配置成使得捕获的光场圆盘图像 201 在正方形栅格上具有整数间距的圆盘，每个圆盘图像 201 包含于正方形的 NxN 区域的源像素 203 内。进一步地，光场图像数据从其“圆盘阵列”呈现置换成其等效的“子孔径图像阵列”呈现，正如 Ng 等人描述的。这种置换可以出现在以下地方中的任何一个或者在任何其它适当的位置：

[0178] ●在传感器 103 本身，使得从传感器 103 读出的原始光场图像数据已经处于其置换布局。

[0179] ●在连接到传感器 103 的处理元件上，诸如照相机的芯片上系统 (SoC)，在照相机的处理流中。

[0180] ●在已经保存到文件中的光场图像数据上。

[0181] 数据的置换可以在原始域（即在数据的解镶嵌之前）中进行，或者在已经转换成全色（例如在 RGB 或 YUV 域中）之后在光场图像数据上进行。

[0182] 在此布局中呈现的光场图像数据可以具有小得多的高频调制。以此布局安排光场图像数据的益处可以包括例如：

[0183] ●如果是 2D 图像，则提高处理光场图像数据的能力，例如对其解镶嵌（在原始光场图像数据的情况下）、对其 JPEG- 编码、视频编码这种帧的序列等等。这是由于以此格式编码的光场图像数据看上去恰好是 2D 图像的图册。当呈现为“圆盘阵列”时，光场图像数据包含高频调制图案，这是由于如果标准 2D 图像算法施加到数据则圆盘图案通常导致数据退化。

[0184] ●更加便宜、高效或快速地执行数据的光场处理的能力。

[0185] 在对用带彩色滤波阵列 (CFA) 的传感器（例如 Bayer 传感器）捕获的原始光场图像数据执行这种置换的情况下，光场图像数据置换后可能在数据范围上不再包含均匀的彩色图案。例如，如图 15 中描绘的，假定光场图像 200 具有 2x2 的圆盘 201，每个圆盘 201 为 3x3 个像素 (N = 3)，则这可以置换成具有 3x3 个子孔径图像的子孔径图像栅格 1503A，每个图像具有 2x2 个像素 203。

[0186] 在另一实施例中，如图 16 中描绘的，CFA 图案可以在传感器上修改，使得光场图像数据、置换后是原始 CFA 图案的合法示例，诸如 Bayer 马赛克图案。在光场图像 200 上执行此操作的一种方式是使用 CFA，CFA 引起每个圆盘图像 201 是均匀的色彩，圆盘图像中的圆盘的彩色图案是合法的马赛克图案。这可以置换成具有 3x3 子孔径图像（每个为 2x2 像素）的子孔径图像栅格 1503B。

[0187] 对于重新聚焦到特定深度的高分辨率的原始置换

[0188] 在至少一个实施例中，光学系统实现为产生具有整数圆盘间距的捕获光场图像，允许在原始 Bayer 域中快速地重新排序捕获的光场图像数据，使得所产生的重新排序的光场图像数据可以直接解释为聚焦在特定深度并使用标准 2D 图像处理算法（包括解镶嵌）处理的 2D 图像，以产生可以显示或输出的最终图像。

[0189] 在至少一个实施例中，光学系统可以表征为如下。

[0190] ●具有正方形包装、整数 N 和适当对齐的微透镜阵列 (MLA) 102。

[0191] ●用于视频和 / 或实时查看设置的光学系统以便能够如下面的方式查看特定的焦平面（在固定焦距的照相机中，此焦平面可以靠近无限焦平面）：

[0192] ●考虑与主透镜 113 的虚拟孔内的位置集合对应的所有子孔径图像的集合，这里，子孔径图像是在“MLA 分辨率”下查看的，原因是在子孔径图像的一行中的像素 203 的数目近似与微透镜阵列 102 的一行中微透镜 201 的数目相同。

[0193] ●定义 L，使得当与虚拟孔的周界周围的点对应的极限子孔径图像各自移动 L/2 个像素，在特定焦平面中焦点的场景物体将在输出图像中的焦点，输出图像是由 Ng 等人描述的“位移 - 和 - 添加”重新聚焦方法形成的。位移方向由在考虑中的特定的焦平面是在光学捕获的焦平面“之前”还是“之后”确定（参见 Ng 等人）。

[0194] ●在操作中，照相机 100 根据下文描述的方法重新聚焦到上文由参数 L 表征的焦平面。

[0195] ● N 和 L 选择为使得 N/L 是整数。使 P ＝ N/L。

[0196] ●传感器具有可以每 NxN 个像素重复一次读取 PxP 像素的单个块的读出模式。

[0197] ●微透镜阵列 102 与传感器 103 对齐，使得每 PxP 的读出块靠近与微透镜阵列 102 对应的像素 203 的圆盘 201 的中心。

[0198] 现在参照图 17A 至 17D，示出了示例性传感器 103，其具有可以每 NxN 个像素 203 重复一次读取 PxP 像素 203 的单个块的读出模式。图 17A 描绘了具有焦平面 1711、微透镜阵列 102 和传感器 103 的光学系统 101A。在图 17A 中，焦平面 1711 和微透镜阵列 102 之间的距离是微透镜阵列 102 和传感器 103 之间的距离的四倍（即 L ＝ 4）。图 17B 描绘了具有 2x2 圆盘 201 的光场图像 200A，每个圆盘 201 有 8x8 像素 (N ＝ 8)。光场图像 200A 可以通过光学系统 101A 的组件产生。图 17C 描绘了光场图像 200A 的子采样图案 1704A。图 17D 描绘了使用子采样图案 1704A 获得的光场图像 200A 的子采样部分 1706A 和相应的置换 1707A(L ＝ N/2)。在置换 1707A 投影中，Bayer 马赛克像素 203 邻近 X/Y 和 U/V 中的邻居以用于解镶嵌。

[0199] 现在参照图 18A 至 18D，示出了另一示例性传感器 103，其具有可以每 NxN 个像素 203 重复一次读取 PxP 像素 203 的单个块的读出模式。图 18A 描绘了具有焦平面 1711、微透镜阵列 102 和传感器 103 的光学系统 101B。在图 18A 中，焦平面 1711 和微透镜阵列 102 之间的距离是微透镜阵列 102 和传感器 103 之间的距离的三倍（即 L ＝ 3)。图 18B 描绘了具有 2x2 圆盘 201 的光场图像 200B，每个圆盘 201 有 9x9 像素 (N ＝ 9)。光场图像 200B 可以通过光学系统 101B 的组件产生。图 18C 描绘了光场图像 200B 的子采样图案 1704B。图 18D 描绘了使用子采样图案 1704B 获得的光场图像 200B 的子采样部分 1706B 和相应的置换 1707B(L ＝ N/3)。在置换 1707B 投影中，Bayer 马赛克像素 203 邻近 X/Y 和 U/V 中的邻居以用于解镶嵌。

[0200] 在操作中，照相机 100 从 PxP 块中子采样图像，并组合所产生的图像。在 L 是正的情况下（在背景中），每个 PxP 块内的像素 203 在中心点上翻转（图 18D)。在 L 为负的情况下，像素 203 保持在当前位置。

[0201] 在至少一个实施例中，所产生的图像具有以下性质：

[0202] ●它聚焦到由参数 L 表征的焦平面上。

[0203] ●所产生图像是 SensorWidth（传感器宽度）*P/N 像素宽、SensorHeight（传感器高度）*P/N 像素高。在 4000x3000 传感器（12MP）的情况下，N ＝ 10，L ＝ 5，输出图像是 800x600 像素。

[0204] ●在所产生的 Bayer 图像中的每个像素 203 邻近在 X/Y 和 U/V 中的邻居。

[0205] ●景深是光学系统的 P 倍，实际上产生具有稍微扩展的景深的图像。

[0206] 这种方法的一个优点是它可以以非常高效的方式产生扩展景深的（EDOF）视频和实时视图。Bayer 马赛克中的投影允许用 X，Y，U，V 空间中的真实邻居来解镶嵌。所述方法还可以产生相对高的分辨率输出。

[0207] 整数间距的六角形微透镜阵列布局

[0208] 在至少一个实施例中，光场光学系统包括微透镜阵列 102，在微透镜阵列 102 上以非矩形晶格（比方说例如六角形晶格）布局微透镜 201，其中，晶格可以在一个维度上（例如垂直地或水平地）拉伸以获得每个维度上的整数间距。例如，如微透镜阵列 102 具有六角形布局，则微透镜间距可以选择为在 N ＝ 10 个像素的传感器上产生水平圆盘间距，但在这种情况下，垂直圆盘间距是 N*SQRT(3)/2 ＝ 8.66 像素。垂直地将微透镜阵列布局拉伸 4％会产生 9 的垂直间距。

[0209] 基于传感器 103 的可用读出模式在传感器 103 之上定位和/或定向微透镜阵列 102

[0210] 在至少一个实施例中，微透镜阵列 102 在传感器 103 上的位置和取向可以基于传感器 103 的读出模式来确定。给定微透镜阵列 102 和图像传感器 103，则可以确定微透镜阵列 102 在图像传感器 103 上的最理想取向和位置。在至少一个实施例中，此取向和位置然后在微透镜阵列 102 被固定到位之前的制造工艺中施加到微透镜阵列 102。

[0211] 现在参照图 19，示出了根据一个实施例的描绘用于确定并配置用在光场图像捕获装置 109 中的微透镜阵列 102 的方法的流程图。此方法将参照图 1A、1B 和 5 中的组件进行描述。

[0212] 首先，访问 1901 微透镜阵列 102 的特征。然后，访问 1902（若干）传感器 103 的特征，包括（若干）传感器 103 的读出模式。基于微透镜阵列 102 的特征和（若干）传感器 103 的特征（包括（若干）图像传感器 103 的读出模式）确定 1903 微透镜阵列 102 的最理想配置。将最理想配置存储 1904 到存储装置，以在光场捕获装置 109 的制造期间施加到微透镜阵列 102。最理想配置例如可以存储在用来制造照相机 100 的制造设备中。

[0213] 在至少一个实施例中，所述系统考虑微透镜阵列 102 围绕与图像传感器平面垂直的轴线（Z- 轴线）的（可能是所有的）物理旋转以及微透镜阵列 102 在与图像传感器平面（XY- 轴线）平行的平面内的所有物理平移的集合。同样，所述系统考虑传感器 103 的所有读出模式的集合（包括例如合并、跳过、重采样、调整和/或其中一些的组合）。对于每种传感器读出模式，微透镜阵列 102 的两个不同的取向/位置可以通过计算和考虑以下因素来比较：

[0214] ●读出像素 203 的平均调制与所有像素 203 的平均调制的比率。例如，假设读出模式根据垂直和水平均为大小 N 的周期性图案跳过像素 203。微透镜阵列 102 的平移相比不平移是优选的，微透镜阵列 102 的平移会最大化在最小调制区域中读出像素 203 的数目。

[0215]　●如果读出模式是分辨率减小的读出模式，则哪部分光场被该读出模式捕获。在每种读出帧中的样本的集合可以相对于其光场坐标来解释。对于特定模式的样本分布的形状可以随微透镜阵列 102 的平移和旋转而变化，一些分布会比另一些分布好。例如，假设根据垂直和水平均为大小 N 的周期性图案，读出模式跳过像素 203，每个光场圆盘图像恰好包含在传感器 103 上的 NxN 像素正方形中。确保中心像素 203 在每个微透镜 102 下读出的微透镜阵列 102 的平移和旋转会产生中心子孔径图像。例如，参见 Ng 等人。

[0216]　●在给定的读出模式下，在由图像传感器 103 施加的任何调整、合并和 / 或重采样期间光场的哪些部分混合在一起。在调整的、合并的或子采样形式的光场图像中的每个输出像素可以计算为传感器像素 203 的组合（可以是加权平均值）。可以用来评估具体的微透镜阵列设置的一个标准是扩展曾用来计算输出像素的传感器像素 203 集合的光场坐标中的方向信息。选择会导致每个输出像素中方向坐标的较大平均扩展的设置可以在输出图像中产生更少的混叠伪影。

[0217]　应对大的主光线角度 (CRA) 的 MLA 设计

[0218]　旨在与远心透镜一起用作主透镜 113 的传感器 103 的性能可以通过使微透镜 201 朝主透镜 113 的光学轴线倾斜来（可能是明显地）改进，使得微透镜 201 接收与其自身的局部表面垂直（或者几乎垂直）的光线。例如，参照图 1B，微透镜阵列 102 中的透镜可以朝主透镜 113 的光学通路倾斜。

[0219]　现在参照图 20，示出了两个示例性微透镜阵列 102 的自上而下的视图。自上而下的视图 2001 描绘了扁平的微透镜阵列 102A。自上而下的视图 2002 描绘了倾斜的微透镜阵列 102B。在自上而下的视图 2002 中，每个微透镜 201 朝光学轴线 (x，y = 0，0) 倾斜。现在再参照图 21，示出了图 20 中描绘的自上而下的视图的示例性 3D 曲线。3D 曲线 2101A 对应于扁平的微透镜阵列 102A。3D 曲线 2101B 对应于倾斜的微透镜阵列 102B。在图 20 和 21 的彩色形式中，红色指示高地势，而蓝色指示低地势。

[0220]　现在参照图 22，示出了通过包含倾斜微透镜 201 的微透镜阵列 102 的示例性 2D 切片 2201。2D 切片 2201 图解说明每个倾斜的微透镜 201 如何结合到其各平面的邻居。如果射线的入射介质是空气，则平面被定向为使得平面平行于来自主透镜 113 的出射光瞳的中心的射线。如果射线的入射介质不是空气，因此具有大于 1 的折射率，平面被定向为使得平面平行于来自主透镜的中心的射线的折射角。这样做是为了最小化由观察者在主透镜 113 的出射光瞳的中心观察到的这些散射表面的效应。可以执行倾斜的 MLA 侧壁角的进一步优化，以便应对主透镜的 f- 数和渐晕以及来自透镜表面的散射、反射和全内反射。

[0221]　现在参照图 23A 和 23B，示出了不同类型的倾斜 MLA 侧壁角优化的两个示例。在图 23A 中，MLA 102 由入射介质 2301（可以是例如玻璃、聚合物或其它透光材料）的底边缘成形，介质 2301 和传感器 103 之间有气隙 2304。从主透镜 113 出射光瞳到达的光线 202 在碰到介质 2301 时折射。MLA 102 的平面 2302 形成并定向为使得匹配入射光的折射角，并且使得这些平面将光线 202 适当地聚焦到传感器 103 上。

[0222]　在图 23B 中，MLA 102 由入射介质 2301 的顶边缘成形，在介质 2301 和传感器 103 之间没有气隙。这里，从主透镜 113 出射光瞳到达的光线 202 在碰到 MLA 102 的平面 2302 之后折射，MLA 102 是由入射介质 2301 的顶边缘形成的。相应地，在此实施例中，平面 2302 成形和定位成使得匹配空气中的入射光的角度，并且使得这些平面将光线 202 适当地聚焦

到传感器 103 上。

[0223] 已经参照可能的实施例特别详细地描述了本发明。本领域技术人员会认识到本发明可以在其它实施例中实践。首先，在组件、词语的大写形式、属性、数据结构或任何其它编程或结构方面的具体命名不是强制性的或重要的，实施本发明或其特征的机构可以具有不同的名字、格式或协议。进一步地，所述系统可以通过如描述的硬件和软件的组合或者整个由硬件元件或者整个由软件元件来实现。同样，本文中描述的各个系统组件之间的功能的特别划分只是示例性的，不是强制性的；由单个系统组件执行的功能实际上可以由多个组件执行，由多个组件执行的功能实际上可以由单个组件执行。

[0224] 在各个实施例中，本发明可以单独地或者以任何组合实现为用于执行上文描述的技术的系统或方法。在另一实施例中，本发明可以实现为一种计算机程序产品，其包括非暂态计算机可读存储介质和在所述介质上编码的计算机程序代码，以用于引起计算装置或其它电子装置中的处理器执行上文描述的技术。

[0225] 在说明书中提到“一个实施例”或“实施例”表示关于该实施例描述的具体特点、结构或特征包括在本发明的至少一个实施例中。在说明书的各个地方出现词语“在至少一个实施例中”不一定全部指相同的实施例。

[0226] 上文的一些部分是根据算法和对计算装置的存储器内的数据位的操作的符号表示呈现的。这些算法描述和呈现是由数据处理领域的技术人员使用以最有效地将他们的工作本质向其他本领域技术人员传递的手段。算法在这里通常构思为是导致期望结果的步骤（指令）的自相一致的序列。步骤为那些需要对物理量进行物理操作的步骤。通常这些量采用能够被存储、传输、组合、比较和另外操作的电、磁或光信号的形式，但不一定是上述形式。有时特别是出于常用原因将这些信号称作位、值、元件、符号、字符、词语、数字等等是方便的。而且，有时在不丧失一般性时将需要对物理量进行物理操作的步骤的某些安排称作模块或代码装置也是方便的。

[0227] 然而，应当记住所有的这些和相似词语与适当的物理量关联，并且这些词语只是应用于这些量的方便标记。除非明确指出，否则如下文的讨论中所显而然见的，要认识到在说明书中，使用诸如“处理”或“计算”或“计划”或“显示”或“确定”等等的词语进行的讨论指计算机系统或类似的电子计算模块和／或装置的动作和处理，所述计算机系统或类似的电子计算模块和／或装置对计算机系统的存储器或寄存器或其它这种信息存储、传输或显示装置内的表示为物理（电子）量的数据进行操作和转换。

[0228] 本发明的某些方面包括在本文中以算法形式描述的处理步骤和指令。应当注意的是，本发明的处理步骤和指令可以体现为软件、固件和／或硬件，当体现为软件时，可以被下载以驻存在由各种不同的操作系统使用的不同平台并由这些平台操作。

[0229] 本发明还涉及一种用于执行本文中的操作的设备。此设备可以具体构造以用于所需目的，或者该设备可以包括被存储在计算装置中的计算机程序选择性激活或重新配置的通用计算装置。这种计算机程序可以存储在计算机可读存储介质中，诸如但不限于任何类型的磁盘，包括软盘、光盘、CD-ROM、磁－光盘、只读存储器 (ROM)、随机存取存储器 (RAM)、EPROM、EEPROM、闪存、固态装置、磁或光学卡、专用集成电路 (ASIC) 或适于存储电子指令并各自耦合到计算机系统总线的任何类型的介质。进一步地，本文中所称的计算装置可以包括单处理器或者可以是为提高计算能力设计的采用多处理器的架构。

[0230] 本文中呈现的算法和显示不固定地涉及任何特定的计算装置、可视化系统或其它设备。各种通用系统也可以根据本文中的教导与程序一起使用，或者构造更加专用的设备以执行所需的方法步骤被证明是方便的。各种各样的这些系统的所需结构从本文中提供的描述是显然的。此外，本发明不是参照任何特定的编程语言描述的。应认识到可以使用各种编程语言以实现如本文中描述的本发明的教导，上文在任何地方提到特定语言是为了公开本发明的实现和最佳方式而提供的。

[0231] 相应地，在各个实施例中，本发明可以实现为软件、硬件和／或用于控制计算机系统、计算装置或其它电子装置的其它元件或其任何组合或多个。根据本领域众所周知的技术，这种电子装置可以包括例如处理器、输入装置（诸如键盘、鼠标、触摸板、跟踪板、操作杆、跟踪球、麦克风和／或其任何组合）、输出装置（诸如屏幕、扬声器等等）、存储器、长期存储（诸如磁存储、光存储等等）和／或网络连接。这种电子装置可以是便携的或非便携的。可以用于实现本发明的电子装置的例子包括：移动电话、个人数字助理、智能手机、电话亭、服务器计算机、企业计算装置、桌面计算机、膝上型计算机、平板电脑、消费电子装置、电视、机顶盒等等。用于实现本发明的电子装置可以使用任何操作系统，比方说例如：Linux；可从华盛顿雷蒙德市的 Microsoft 公司购买的 Microsoft Windows；可从加利福尼亚的库珀蒂诺 (Cupertino) 的苹果公司购买的 Mac OS X；可从加利福尼亚的库珀蒂诺的苹果公司购买的 iOS 和／或适于用在这些装置上的其它任何操作系统。

[0232] 尽管已经参照有限个实施例描述了本发明，但本领域技术人员受益于上文的描述会认识到可以设计不偏离如本文中描述的本发明的范围的其它实施例。此外，应当注意说明书中使用的语言主要是为可读性和教授目的而选择的，不是为限定或限制本发明的主题而选择的。相应地，本发明的公开想要是示意而不是限定在权利要求中陈述的本发明的范围。

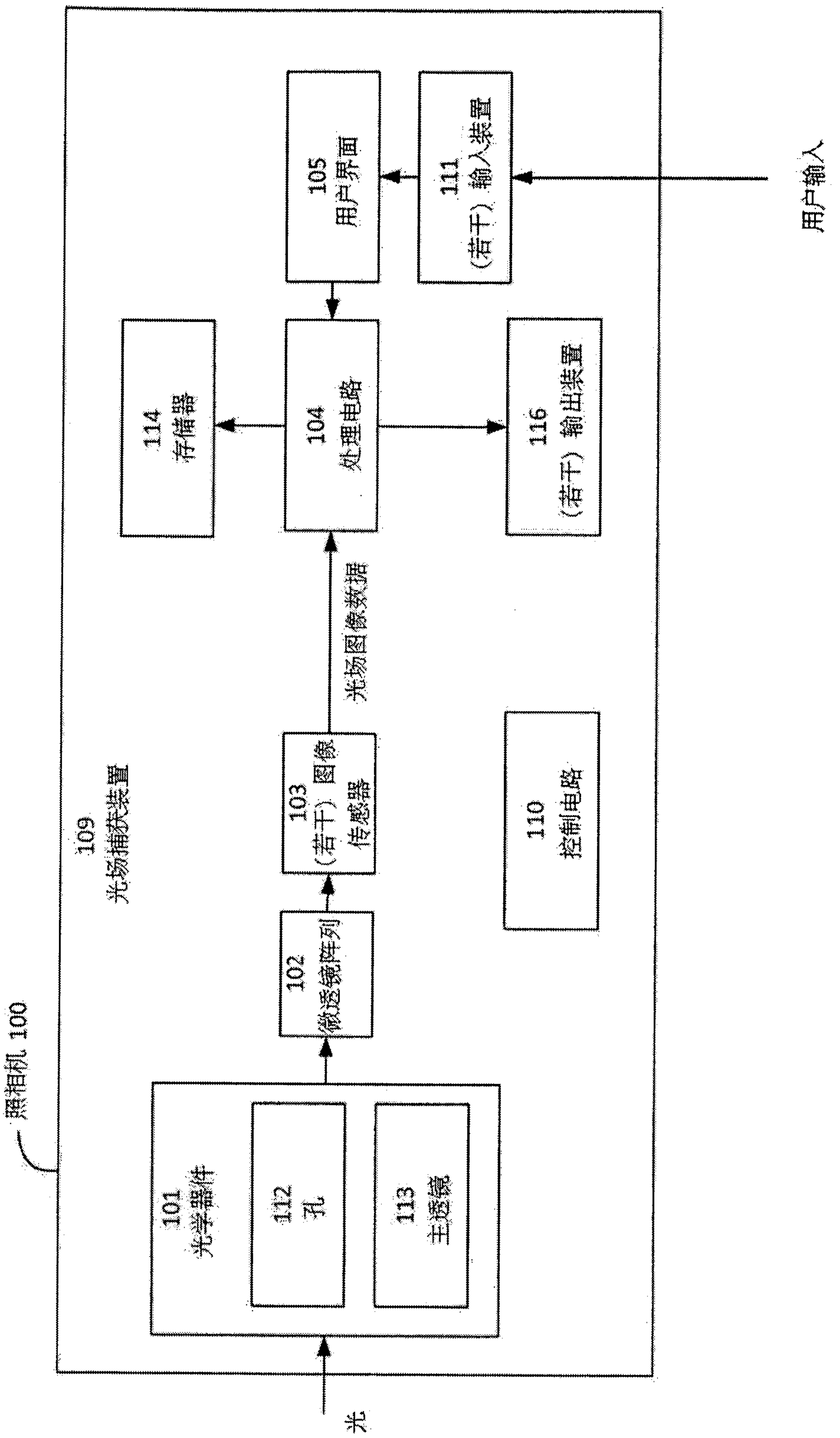

照相机 100
109
光场捕获装置
101
光学器件
112
孔
113
主透镜
102
微透镜阵列
103
（若干）图像
传感器
光场图像数据
104
处理电路
114
存储器
116
（若干）输出装置
105
用户界面
111
（若干）输入装置
用户输入
110
控制电路
光

图 1A

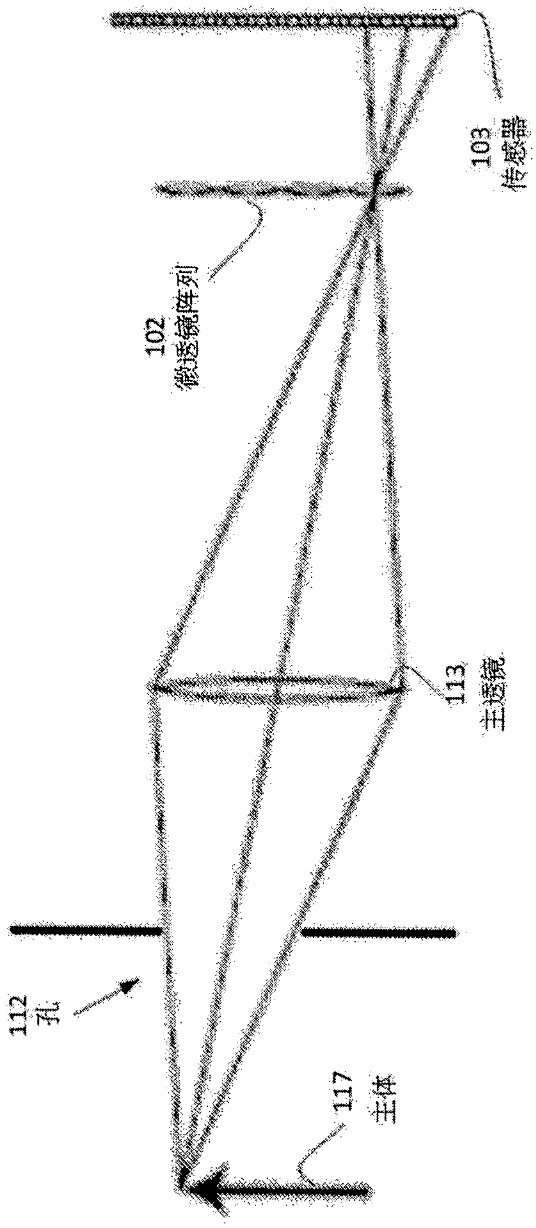


图 1B

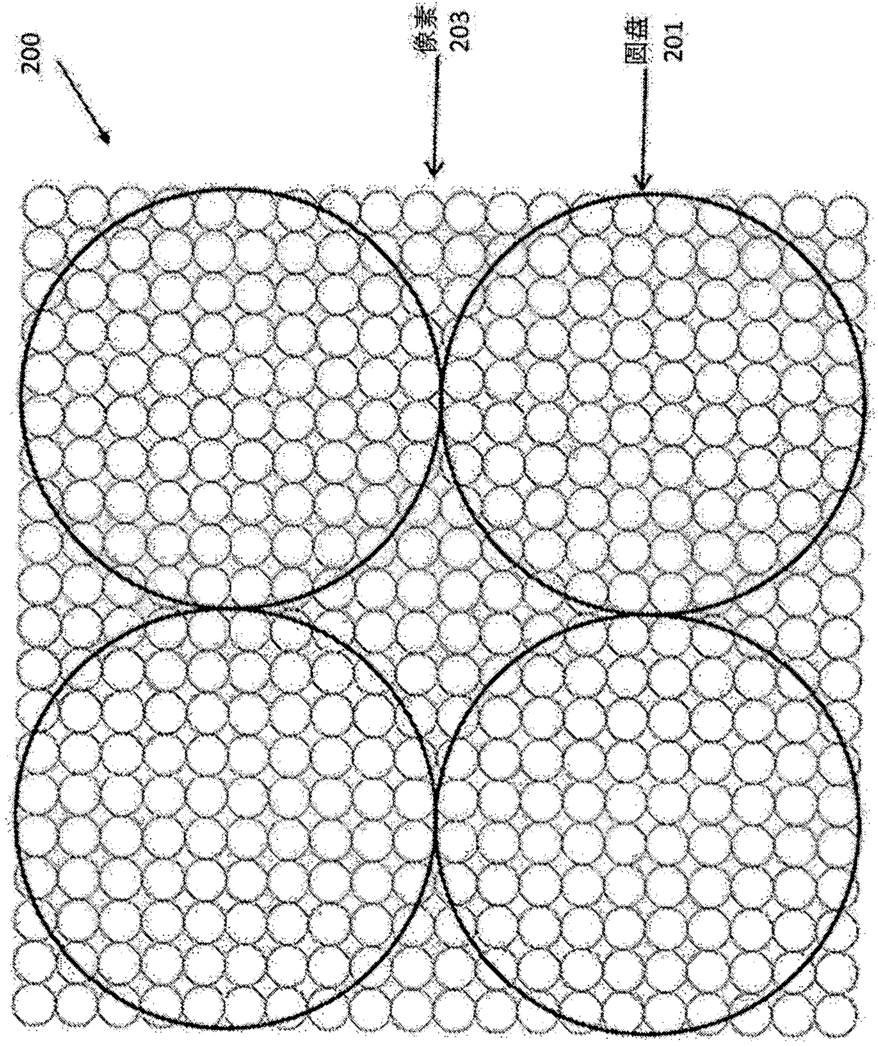


图 2

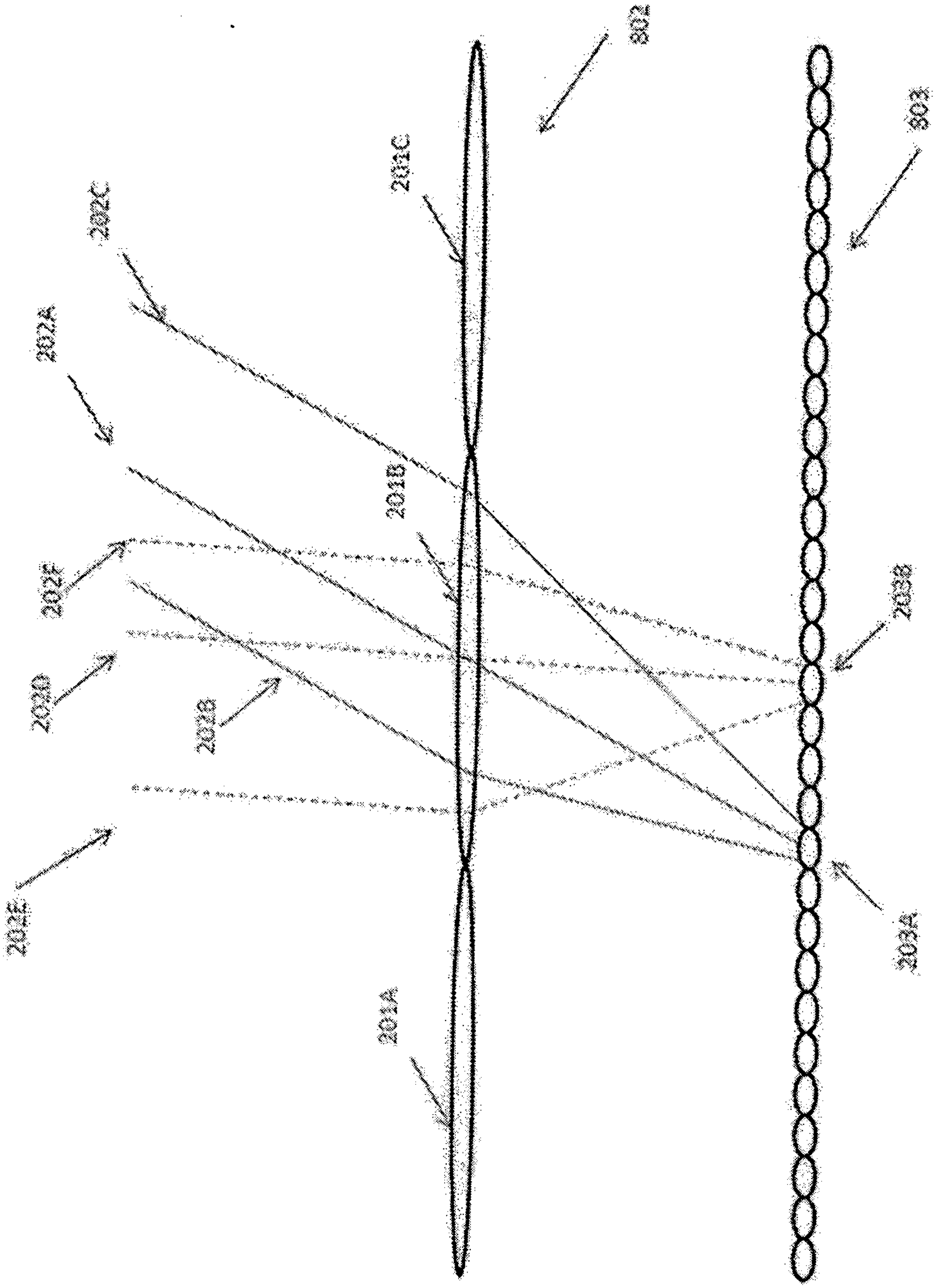

802
803
201C
202C
202A
201B
202F
203B
202D
201E
202E
203A
201A

图 3A

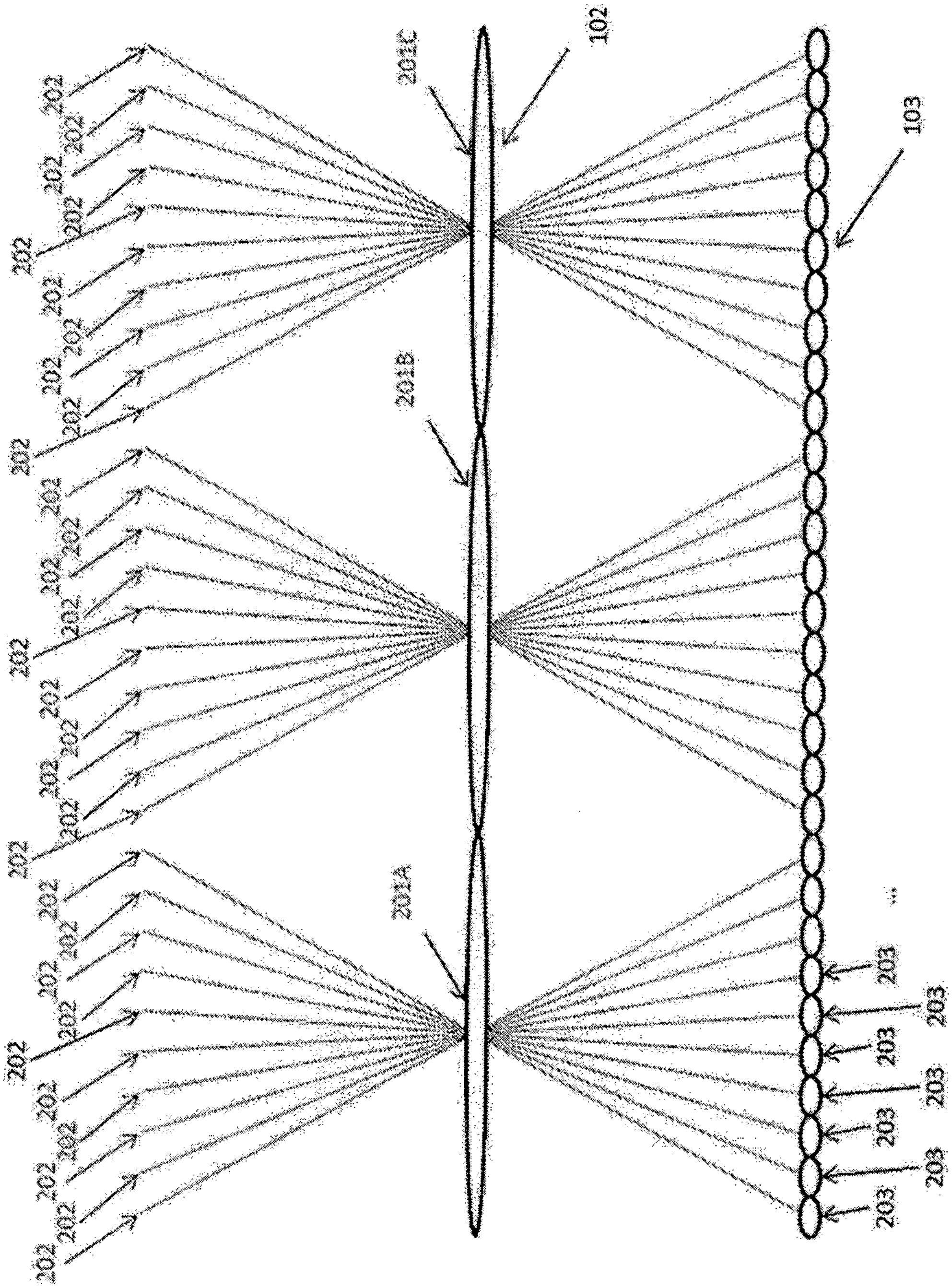


图 3B

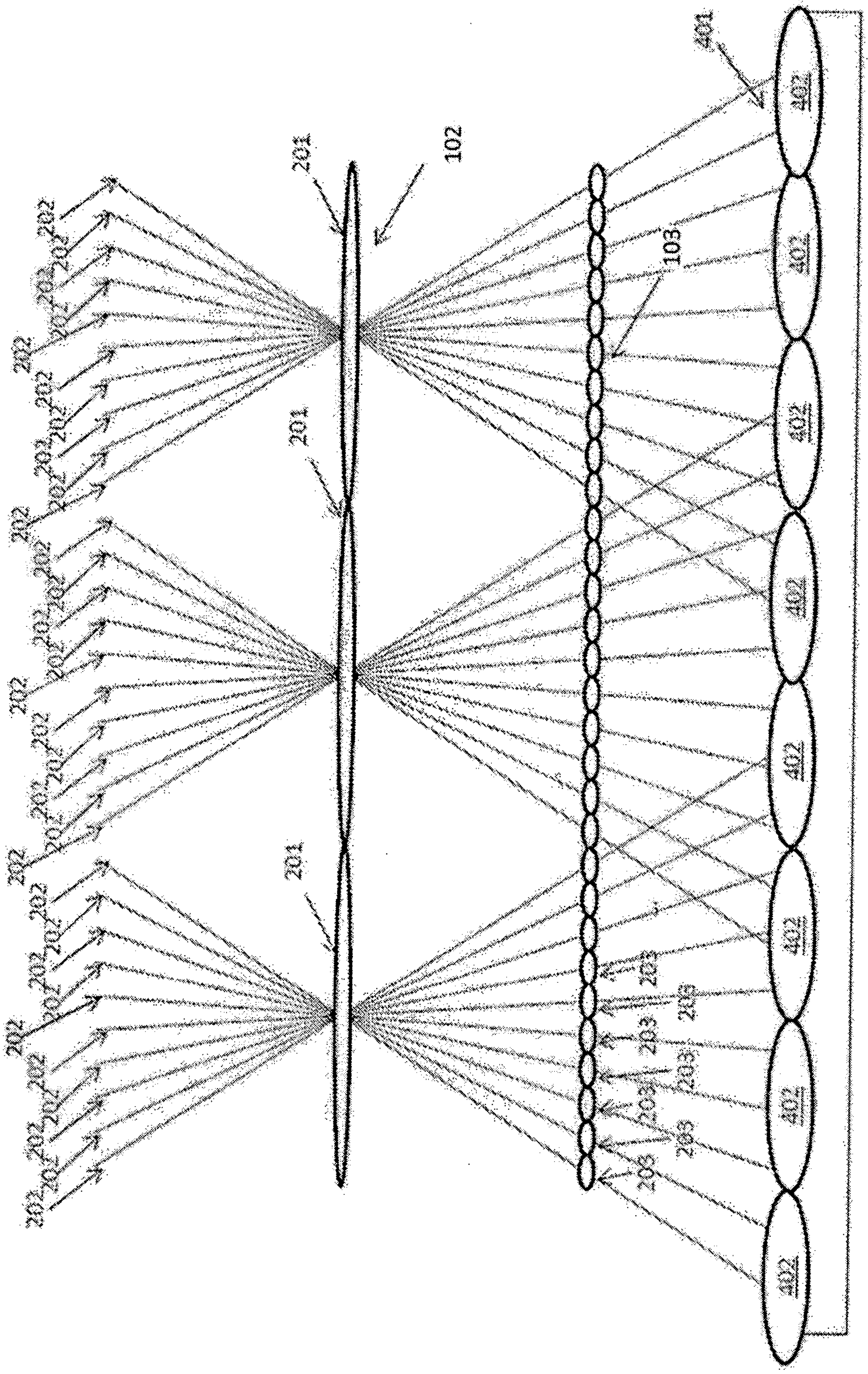


图 4

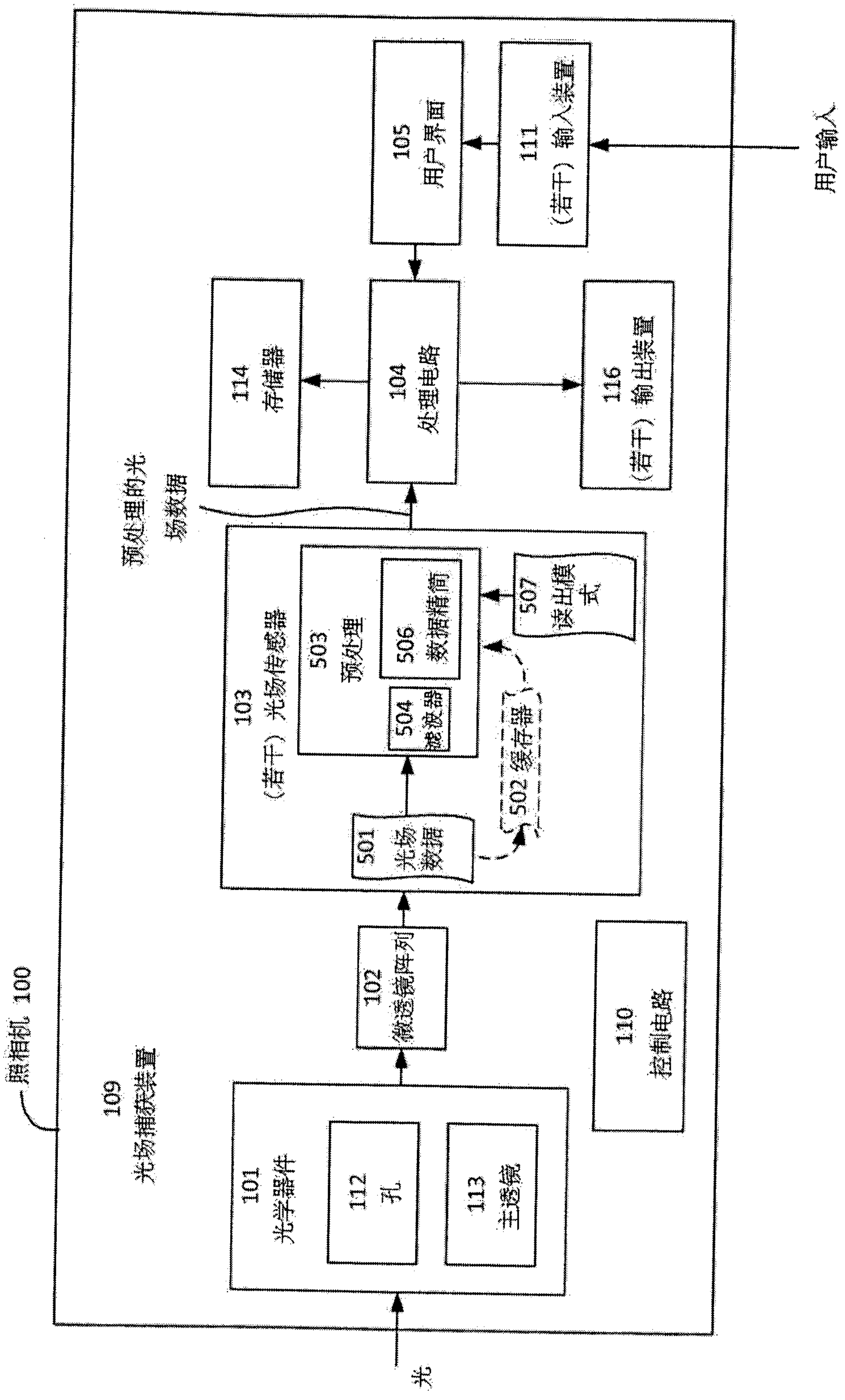

照相机 100
109
光场捕获装置
101
光学器件
112
孔
113
主透镜
102
微透镜阵列
103
（若干）光场传感器
501
光场
数据
502 缓存器
503
预处理
504
滤波器
506
数据精简
507
读出模
式
预处理的光
场数据
104
处理电路
114
存储器
116
（若干）输出装置
105
用户界面
111
（若干）输入装置
用户输入
110
控制电路
光

图 5

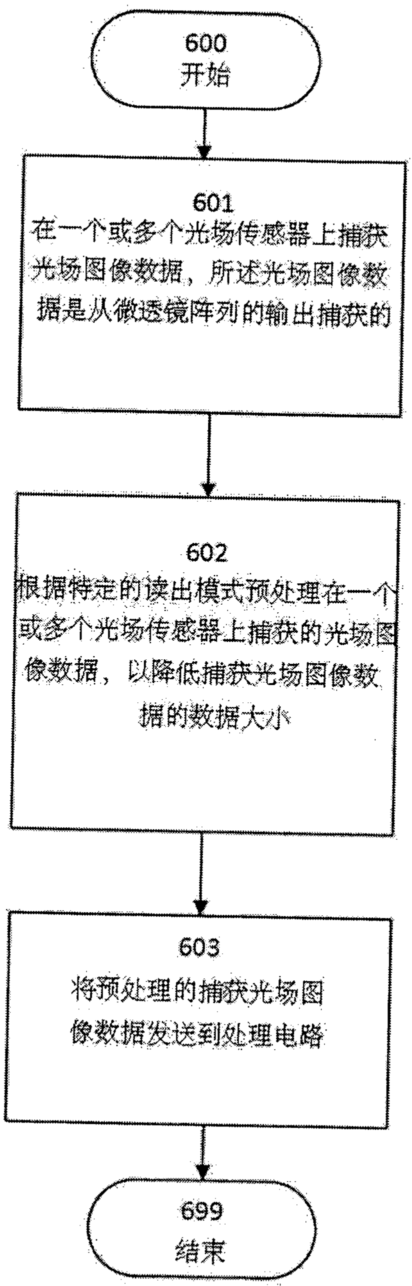

600
开始
601
在一个或多个光场传感器上捕获光场图像数据，所述光场图像数据是从微透镜阵列的输出捕获的
602
根据特定的读出模式预处理在一个或多个光场传感器上捕获的光场图像数据，以降低捕获光场图像数据的数据大小
603
将预处理的捕获光场图像数据发送到处理电路
699
结束

图 6

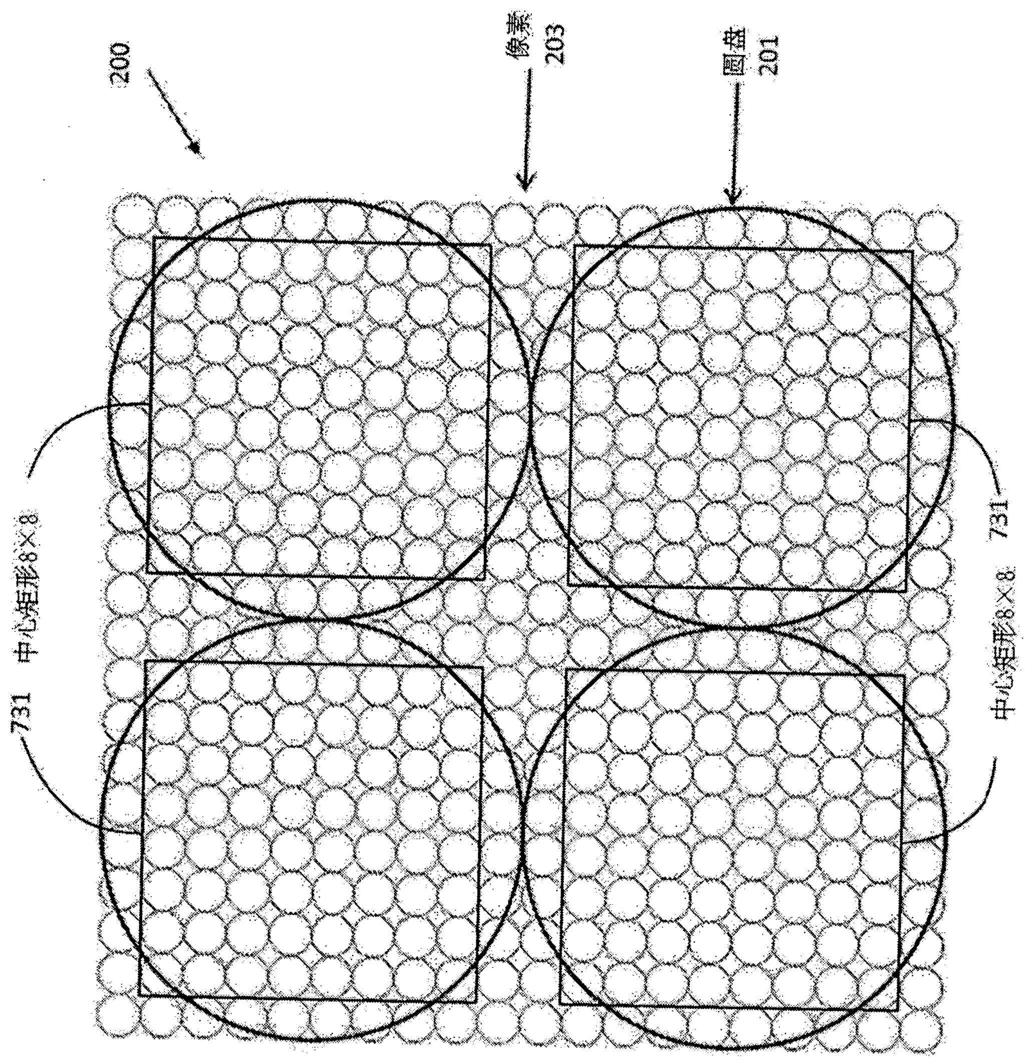


图 7

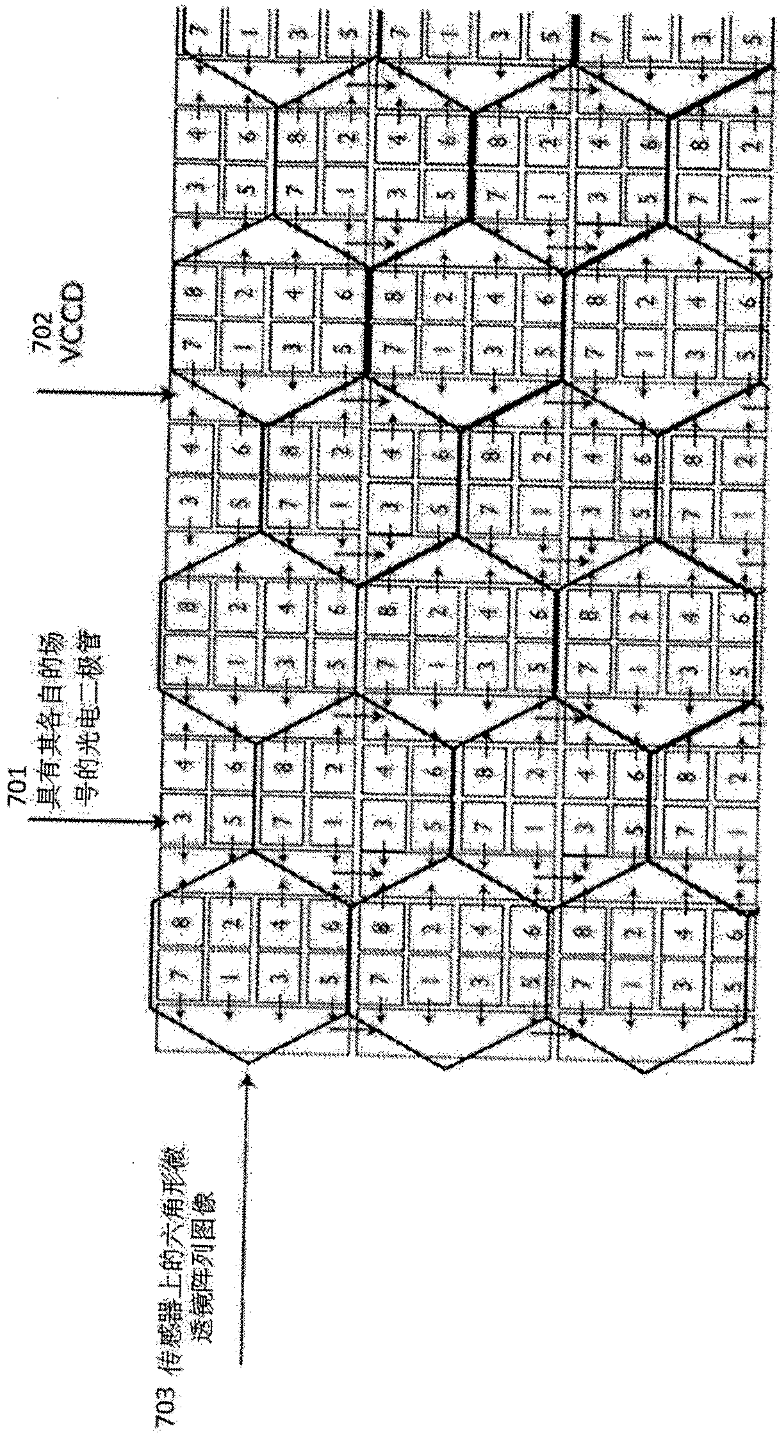


图 8

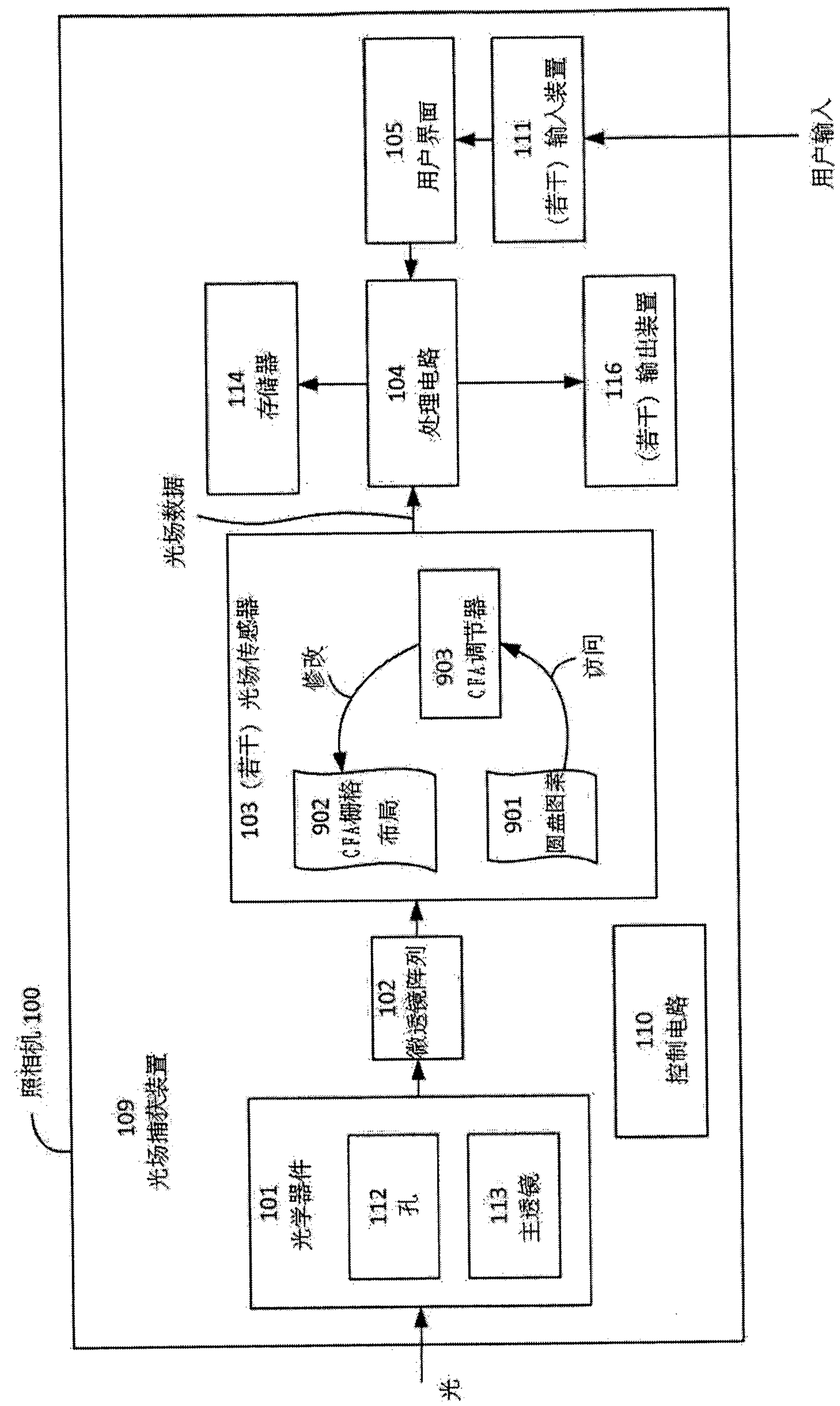

照相机 100
109
光场捕获装置
101
光学器件
112
孔
113
主透镜
102
微透镜阵列
103（若干）光场传感器
902
CFA栅格
布局
901
图盘图案
903
CFA调节器
修改
访问
光场数据
104
处理电路
114
存储器
116
（若干）输出装置
105
用户界面
111
（若干）输入装置
用户输入
110
控制电路
光

图 9

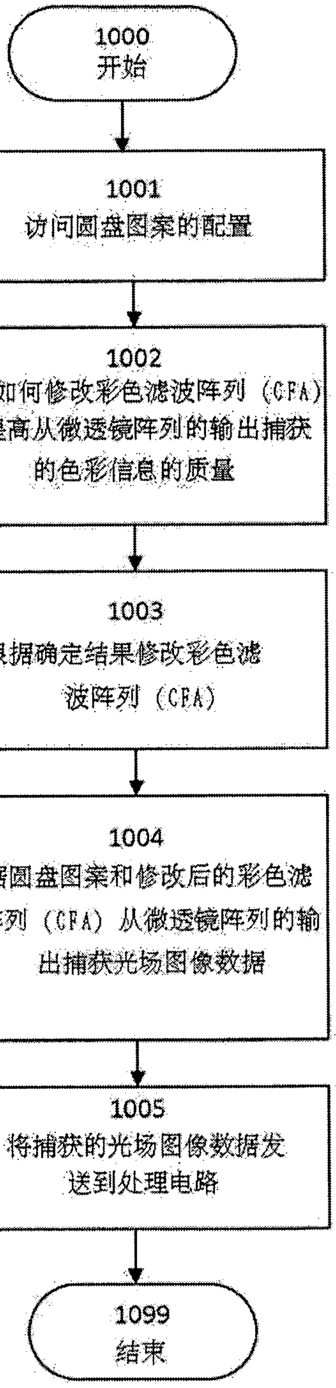

1000
开始
1001
访问圆盘图案的配置
1002
确定如何修改彩色滤波阵列（CFA）以提高从微透镜阵列的输出捕获的色彩信息的质量
1003
根据确定结果修改彩色滤波阵列（CFA）
1004
根据圆盘图案和修改后的彩色滤波阵列（CFA）从微透镜阵列的输出捕获光场图像数据
1005
将捕获的光场图像数据发送到处理电路
1099
结束

图 10

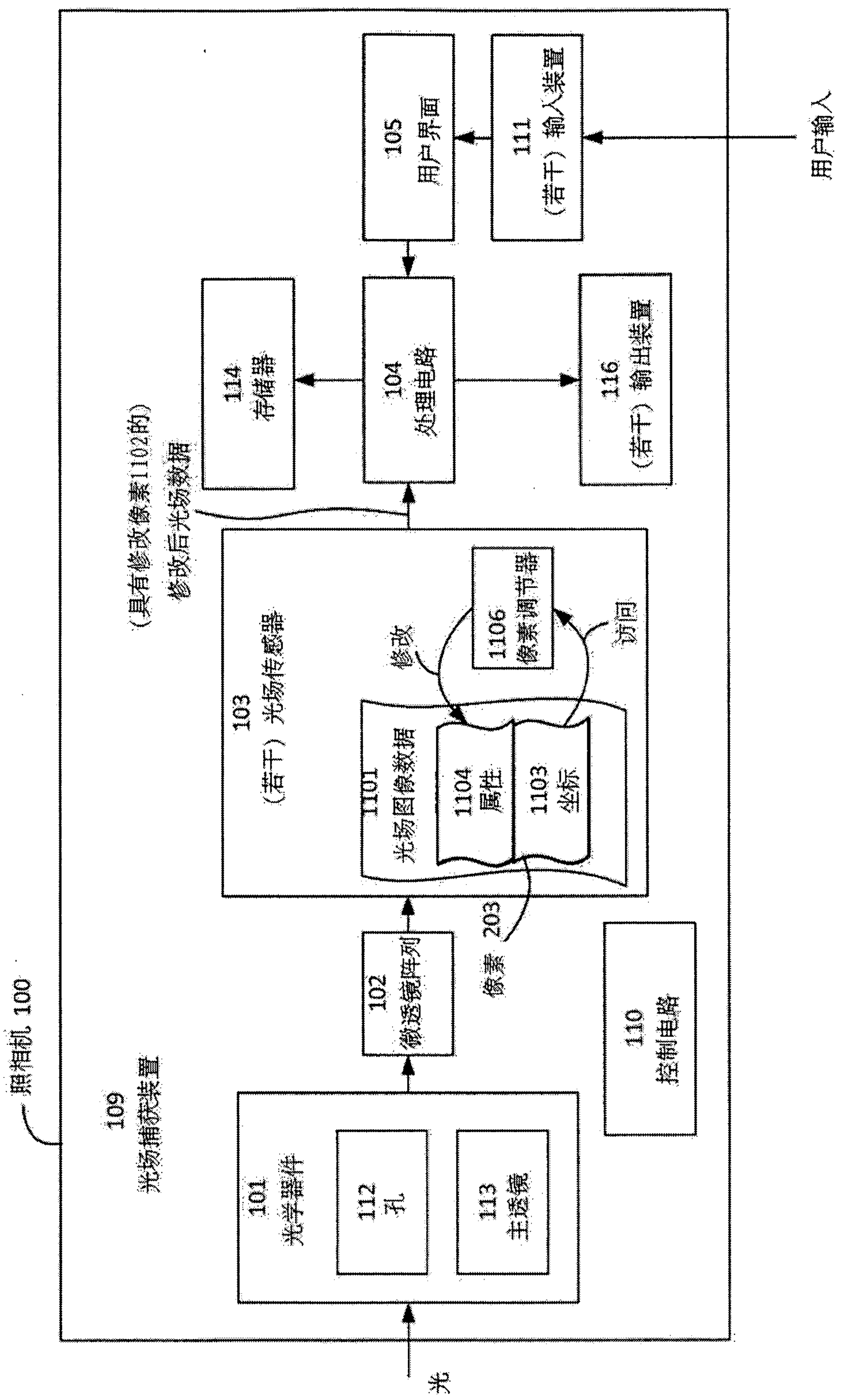

照相机 100
109
光场捕获装置
101
光学器件
112
孔
113
主透镜
102
微透镜阵列
103
（若干）光场传感器
1101
光场图像数据
1104
属性
1103
坐标
1106
像素调节器
修改
访问
像素 203
110
控制电路
（具有修改像素1102的）
修改后光场数据
104
处理电路
114
存储器
116
（若干）输出装置
105
用户界面
111
（若干）输入装置
用户输入
光

图 11

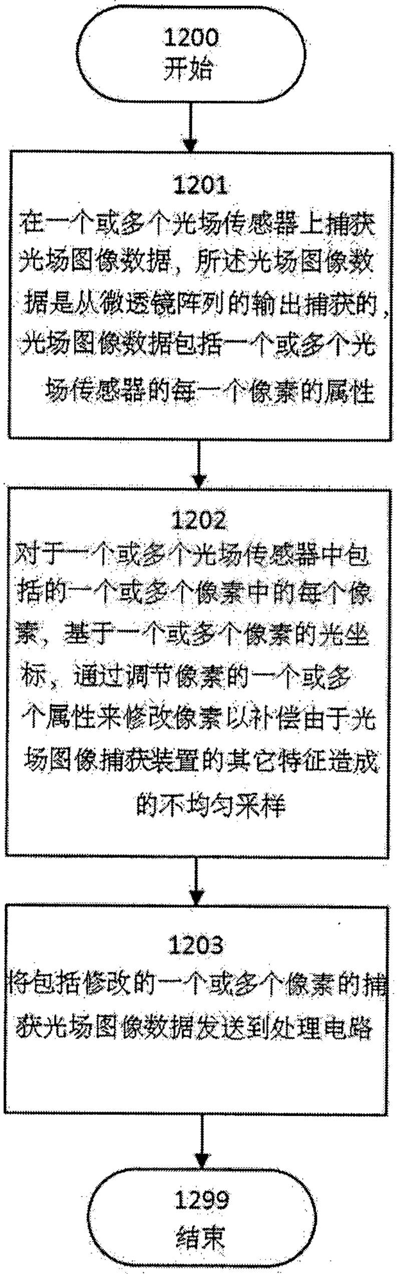
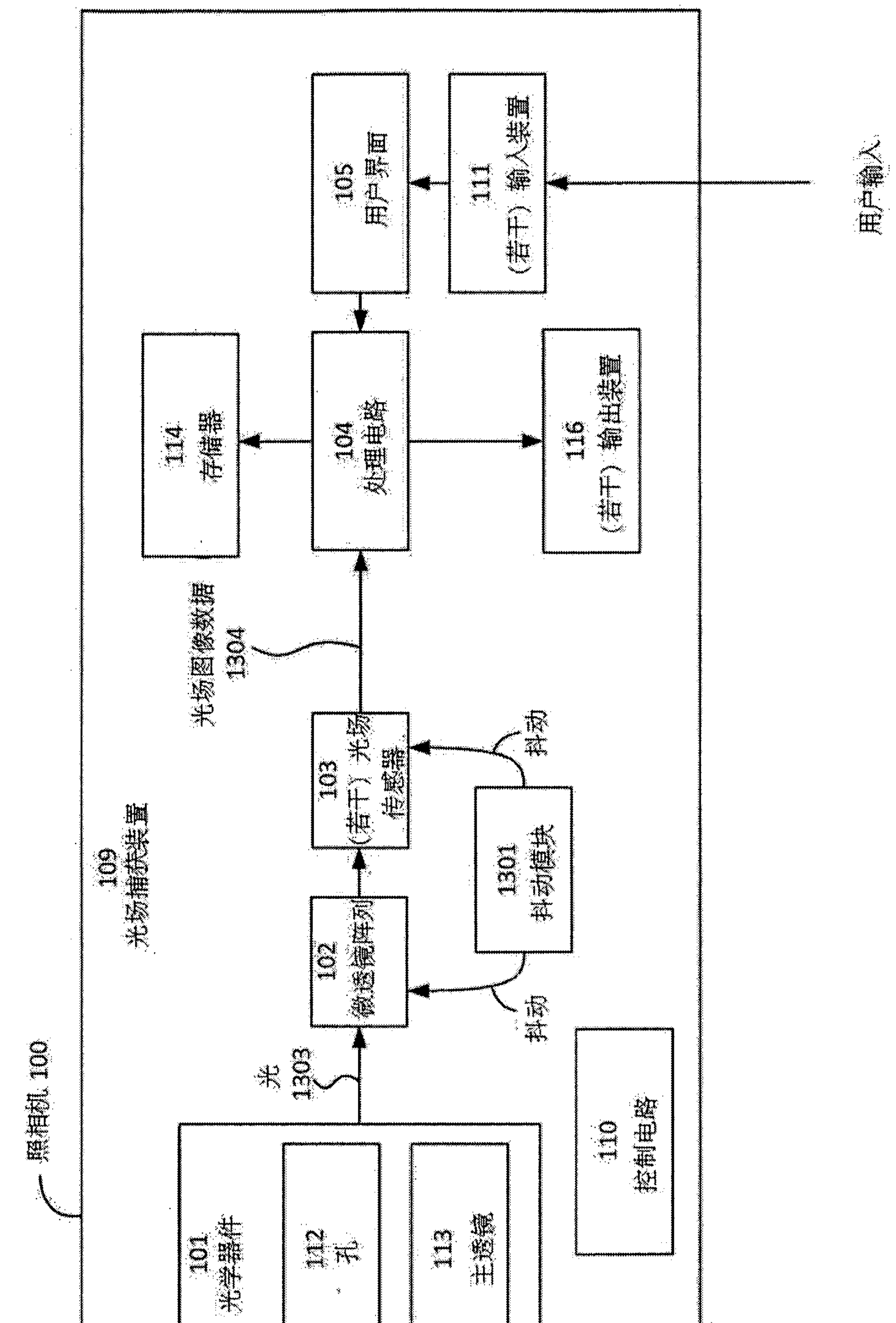

1200
开始
1201
在一个或多个光场传感器上捕获光场图像数据，所述光场图像数据是从微透镜阵列的输出捕获的，光场图像数据包括一个或多个光场传感器的每一个像素的属性
1202
对于一个或多个光场传感器中包括的一个或多个像素中的每个像素，基于一个或多个像素的光坐标，通过调节像素的一个或多个属性来修改像素以补偿由于光场图像捕获装置的其它特征造成的不均匀采样
1203
将包括修改的一个或多个像素的捕获光场图像数据发送到处理电路
1299
结束

图 12



照相机 100
109
光场捕获装置
101
光学器件
112
孔
113
主透镜
光
1302
光
1303
102
微透镜阵列
103
(若干) 光场
传感器
1301
抖动模块
抖动
抖动
光场图像数据
1304
104
处理电路
114
存储器
116
(若干) 输出装置
105
用户界面
111
(若干) 输入装置
用户输入
110
控制电路

图 13

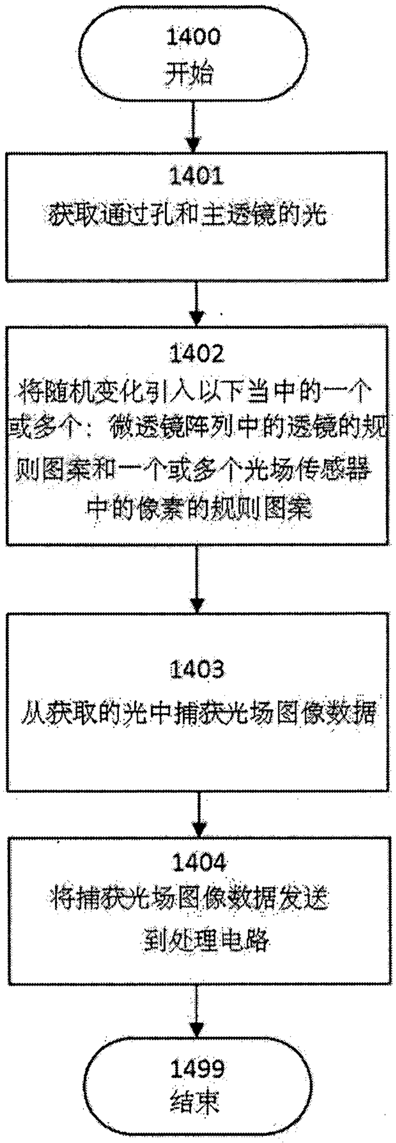

1400
开始
1401
获取通过孔和主透镜的光
1402
将随机变化引入以下当中的一个或多个：微透镜阵列中的透镜的规则图案和一个或多个光场传感器中的像素的规则图案
1403
从获取的光中捕获光场图像数据
1404
将捕获光场图像数据发送到处理电路
1499
结束

图 14

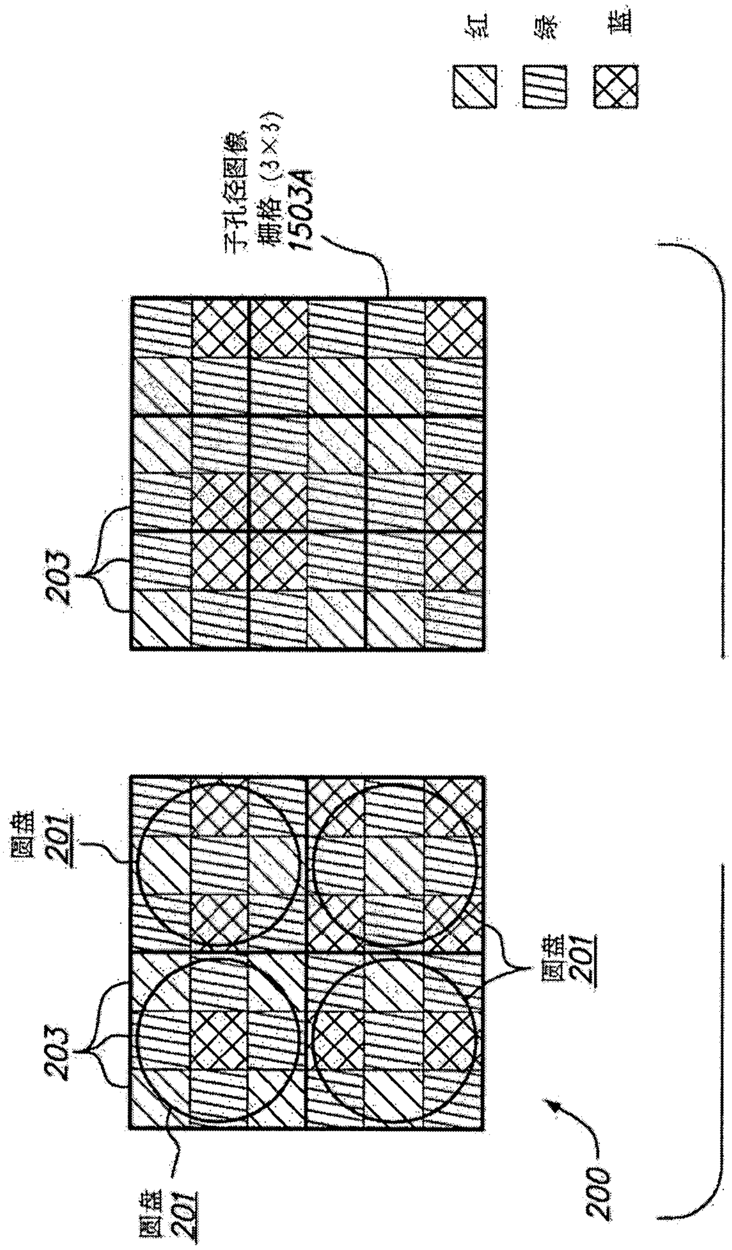


图 15

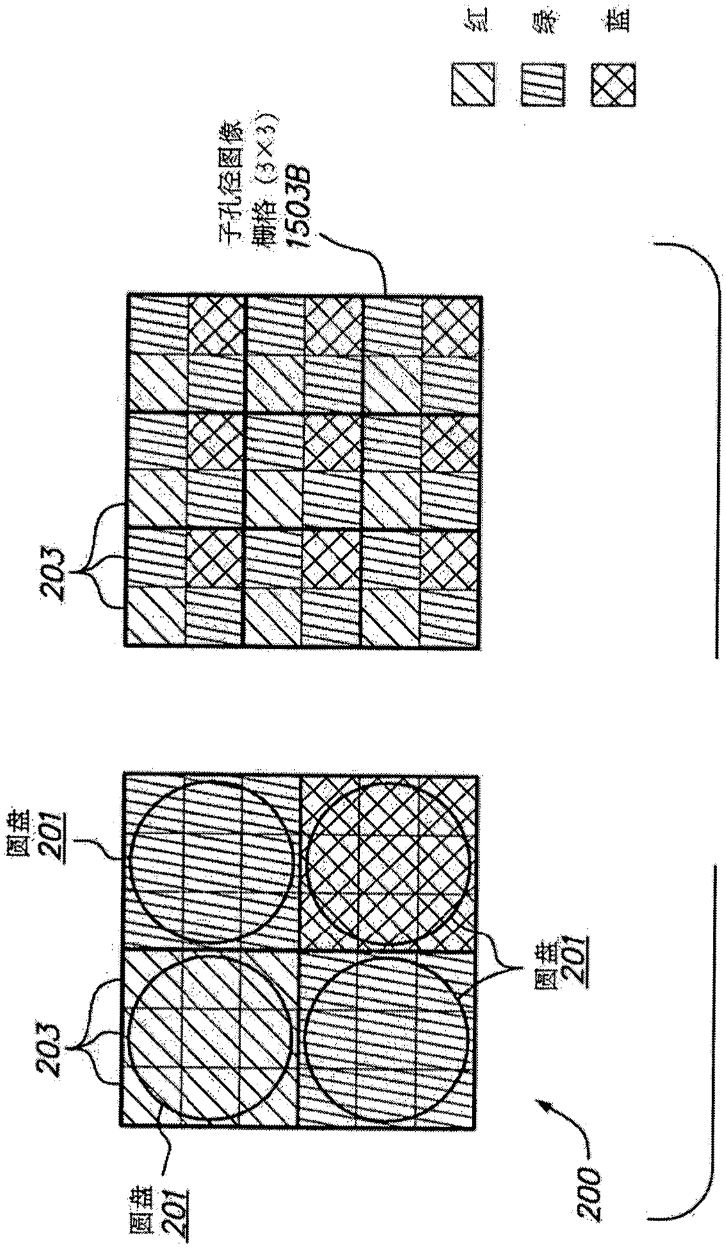


图 16

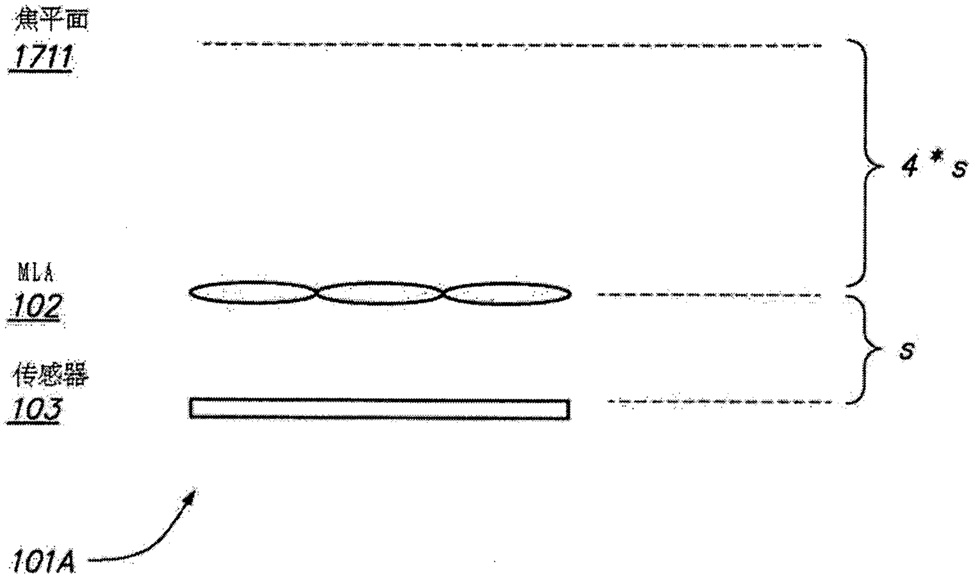


图 17A

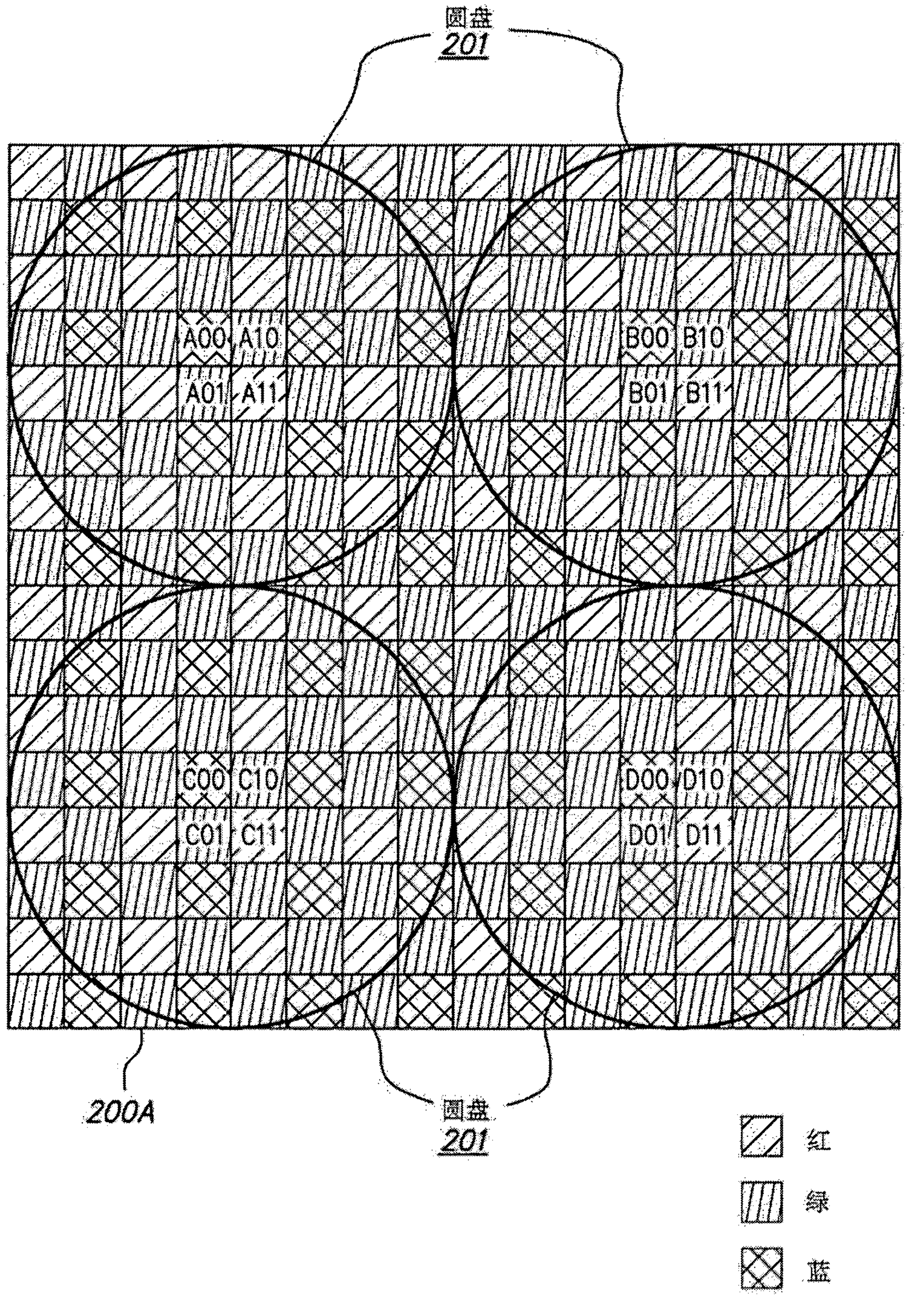
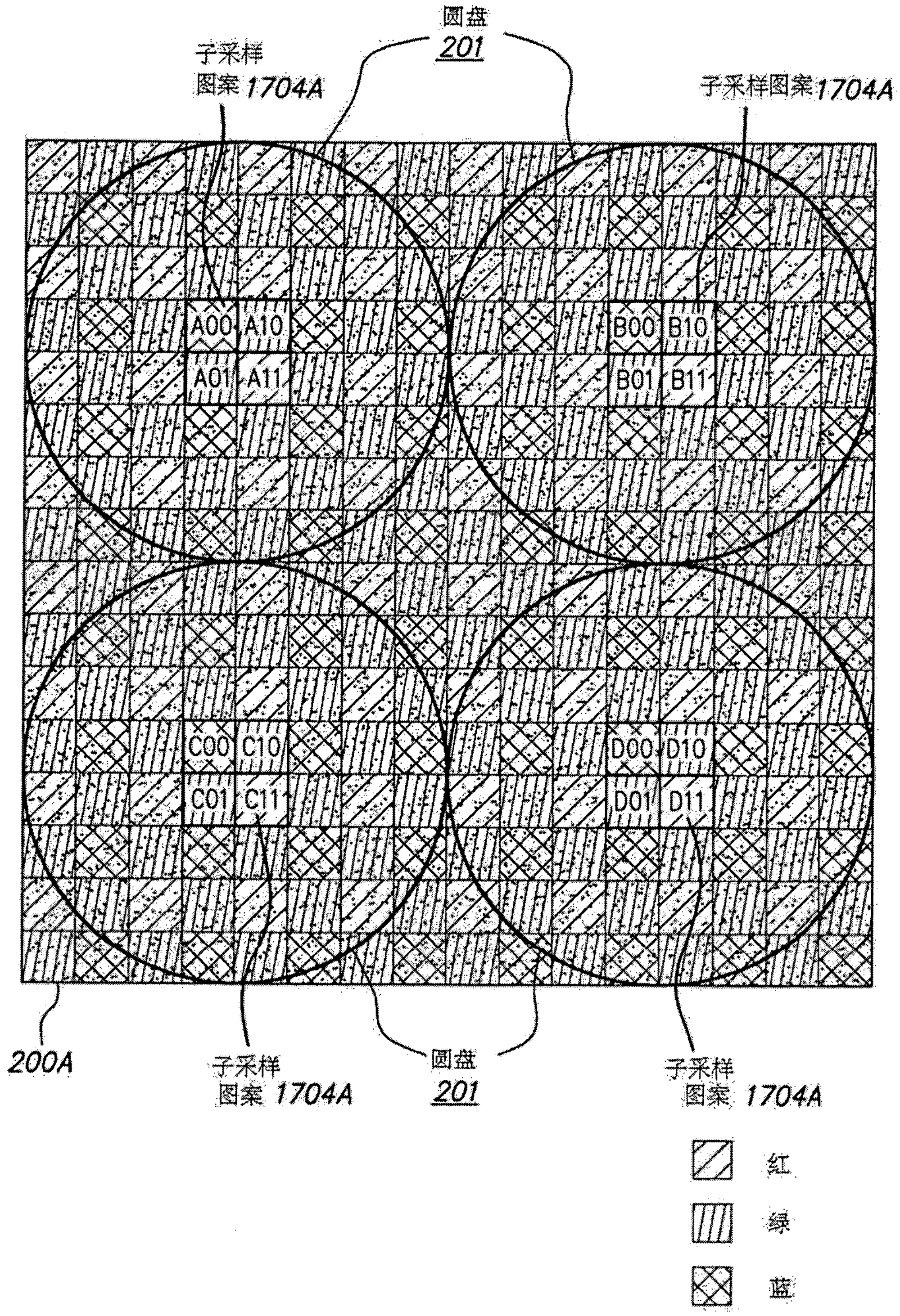

圆盘
201
A00 A10
A01 A11
B00 B10
B01 B11
C00 C10
C01 C11
D00 D10
D01 D11
200A
圆盘
201
红
绿
蓝

图 17B



圆盘
201
子采样
图案 1704A
子采样图案 1704A
A00
A10
A01
A11
B00
B10
B01
B11
C00
C10
C01
C11
D00
D10
D01
D11
200A
子采样
图案 1704A
圆盘
201
子采样
图案 1704A
红
绿
蓝

图 17C

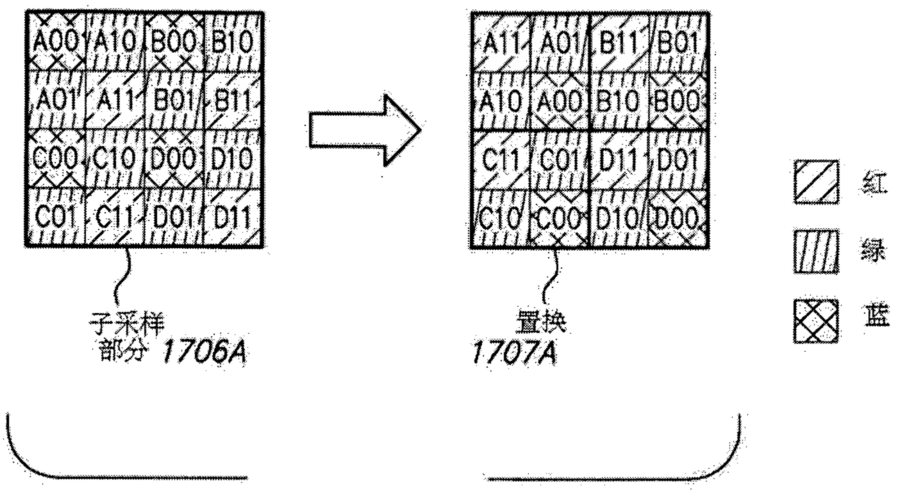

A00 A10 B00 B10
A01 A11 B01 B11
C00 C10 D00 D10
C01 C11 D01 D11
子采样部分 1706A
A11 A01 B11 B01
A10 A00 B10 B00
C11 C01 D11 D01
C10 C00 D10 D00
置换 1707A
红
绿
蓝

图 17D

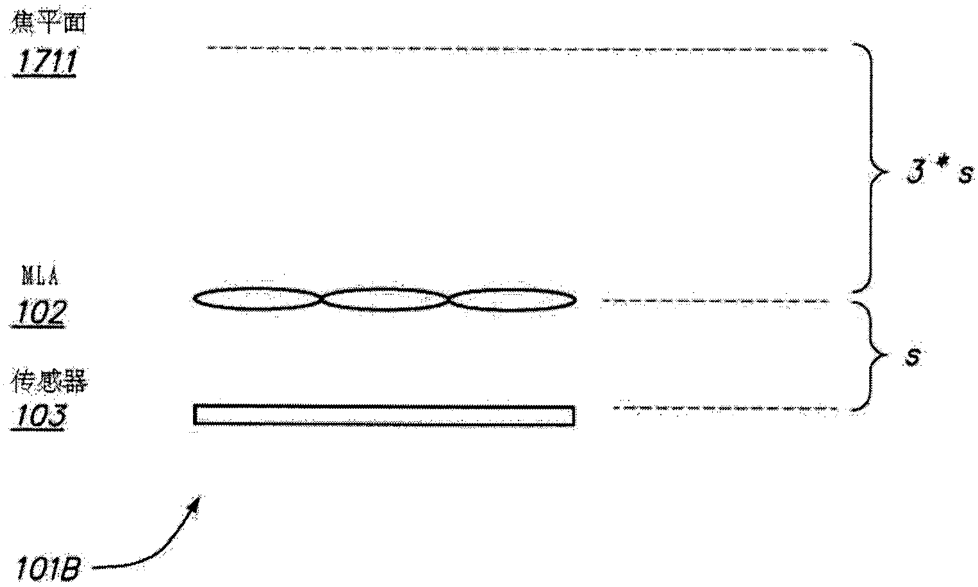

焦平面 1711
3 * s
MLA 102
s
传感器 103
101B

图 18A

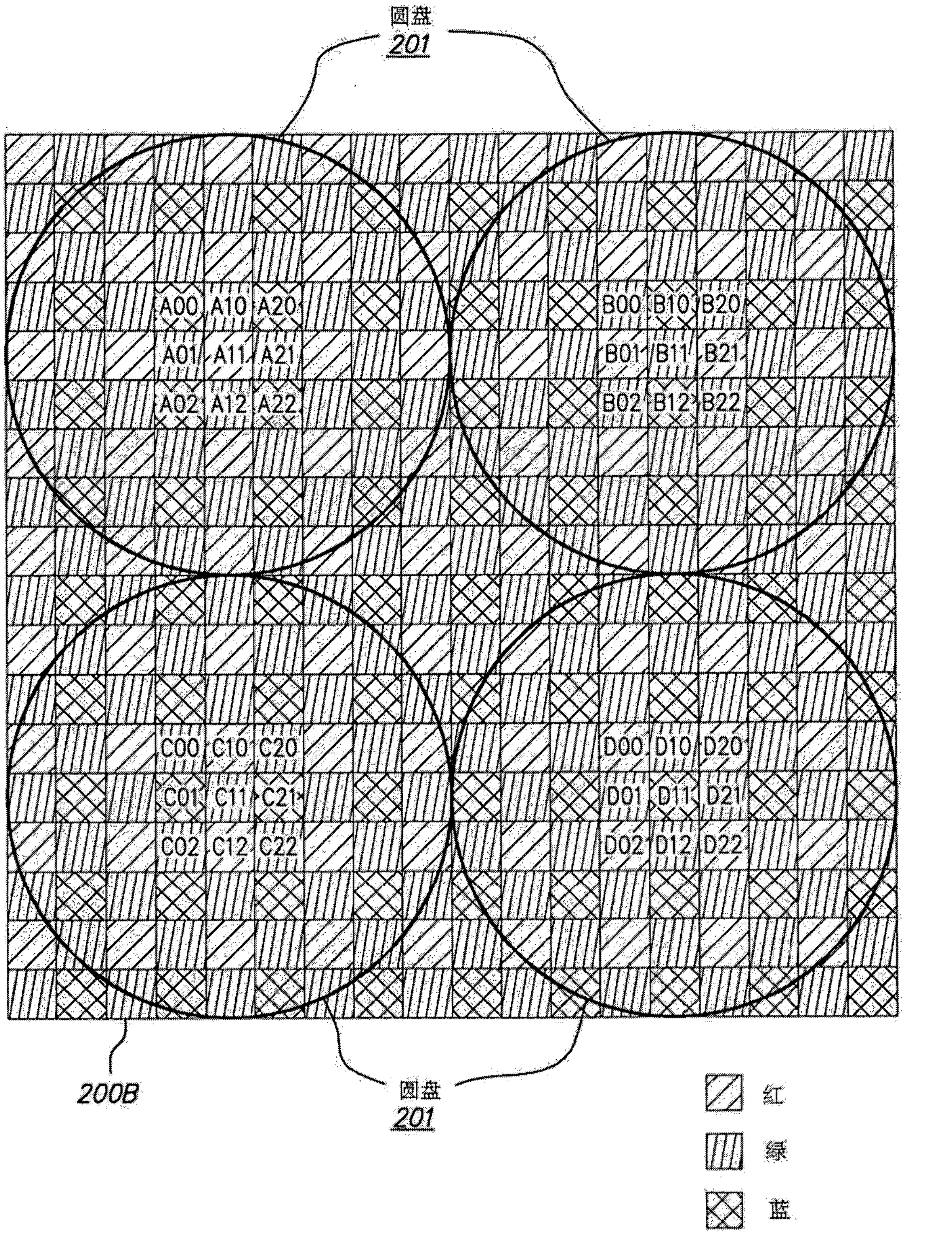

圆盘
201
A00 A10 A20
A01 A11 A21
A02 A12 A22
B00 B10 B20
B01 B11 B21
B02 B12 B22
C00 C10 C20
C01 C11 C21
C02 C12 C22
D00 D10 D20
D01 D11 D21
D02 D12 D22
200B
圆盘
201
红
绿
蓝

图 18B

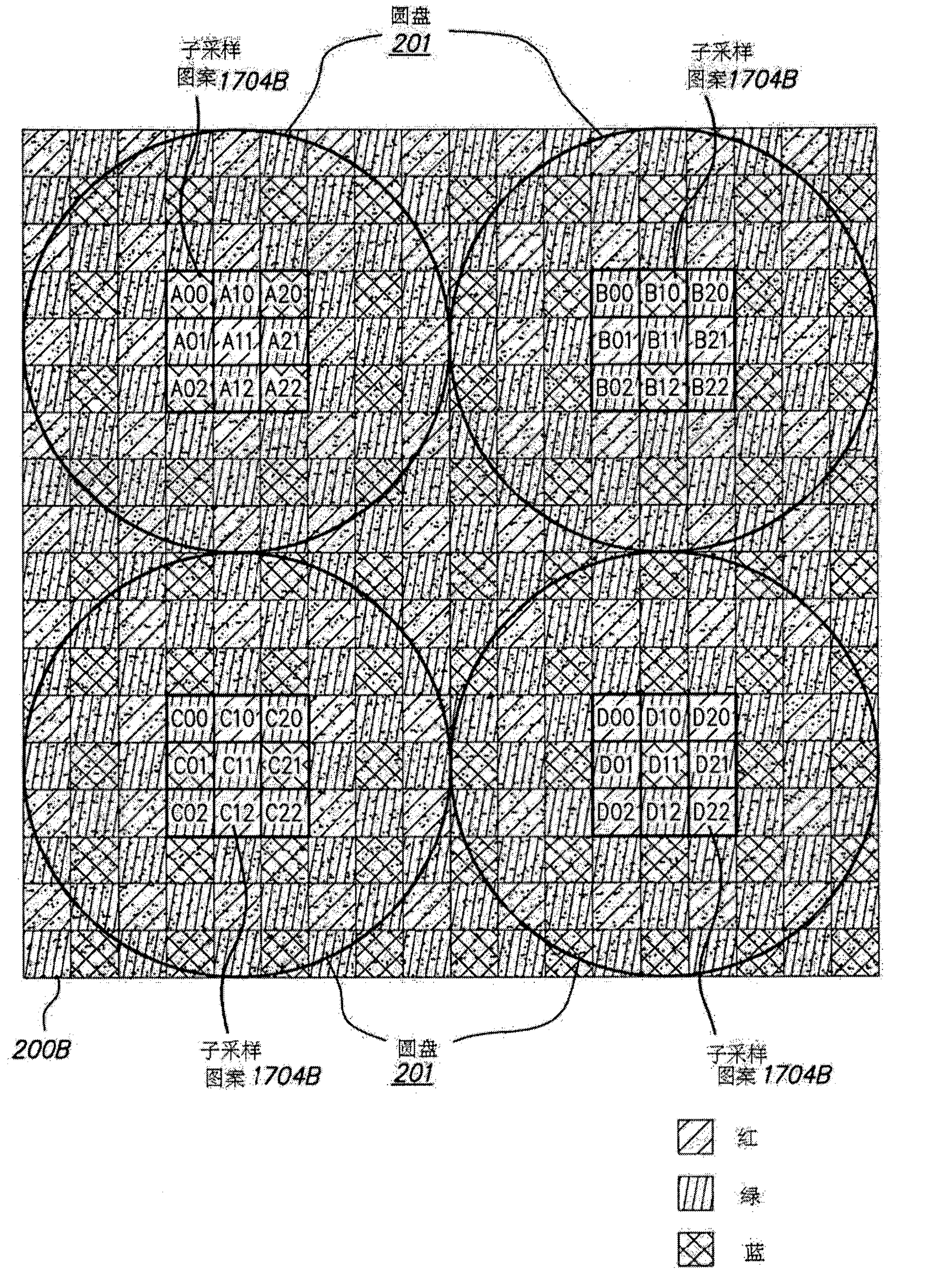

圆盘
201
子采样
图案1704B
子采样
图案1704B
A00 A10 A20
A01 A11 A21
A02 A12 A22
B00 B10 B20
B01 B11 B21
B02 B12 B22
C00 C10 C20
C01 C11 C21
C02 C12 C22
D00 D10 D20
D01 D11 D21
D02 D12 D22
200B
子采样
图案1704B
圆盘
201
子采样
图案1704B
红
绿
蓝

图 18C

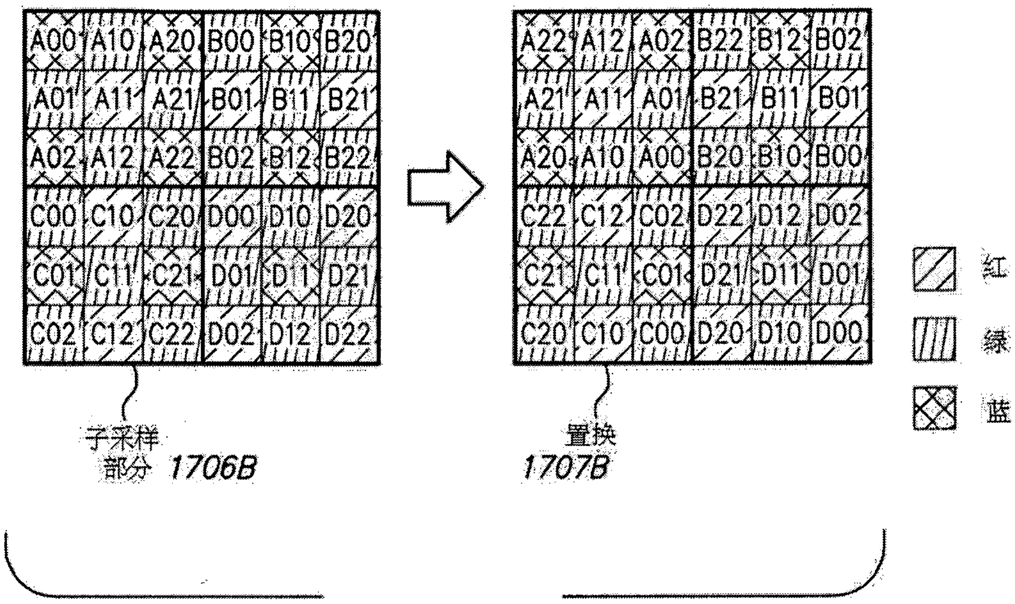

A00 A10 A20 B00 B10 B20
A01 A11 A21 B01 B11 B21
A02 A12 A22 B02 B12 B22
C00 C10 C20 D00 D10 D20
C01 C11 C21 D01 D11 D21
C02 C12 C22 D02 D12 D22
A22 A12 A02 B22 B12 B02
A21 A11 A01 B21 B11 B01
A20 A10 A00 B20 B10 B00
C22 C12 C02 D22 D12 D02
C21 C11 C01 D21 D11 D01
C20 C10 C00 D20 D10 D00
红
绿
蓝
子采样部分 1706B
置换 1707B

图 18D

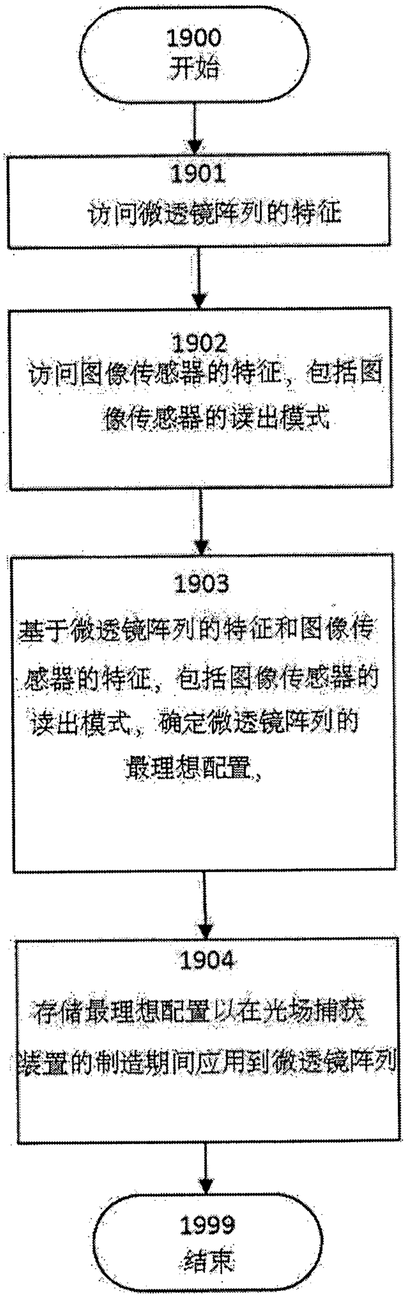

1900
开始
1901
访问微透镜阵列的特征
1902
访问图像传感器的特征，包括图像传感器的读出模式
1903
基于微透镜阵列的特征和图像传感器的特征，包括图像传感器的读出模式，确定微透镜阵列的最理想配置，
1904
存储最理想配置以在光场捕获装置的制造期间应用到微透镜阵列
1999
结束

图 19

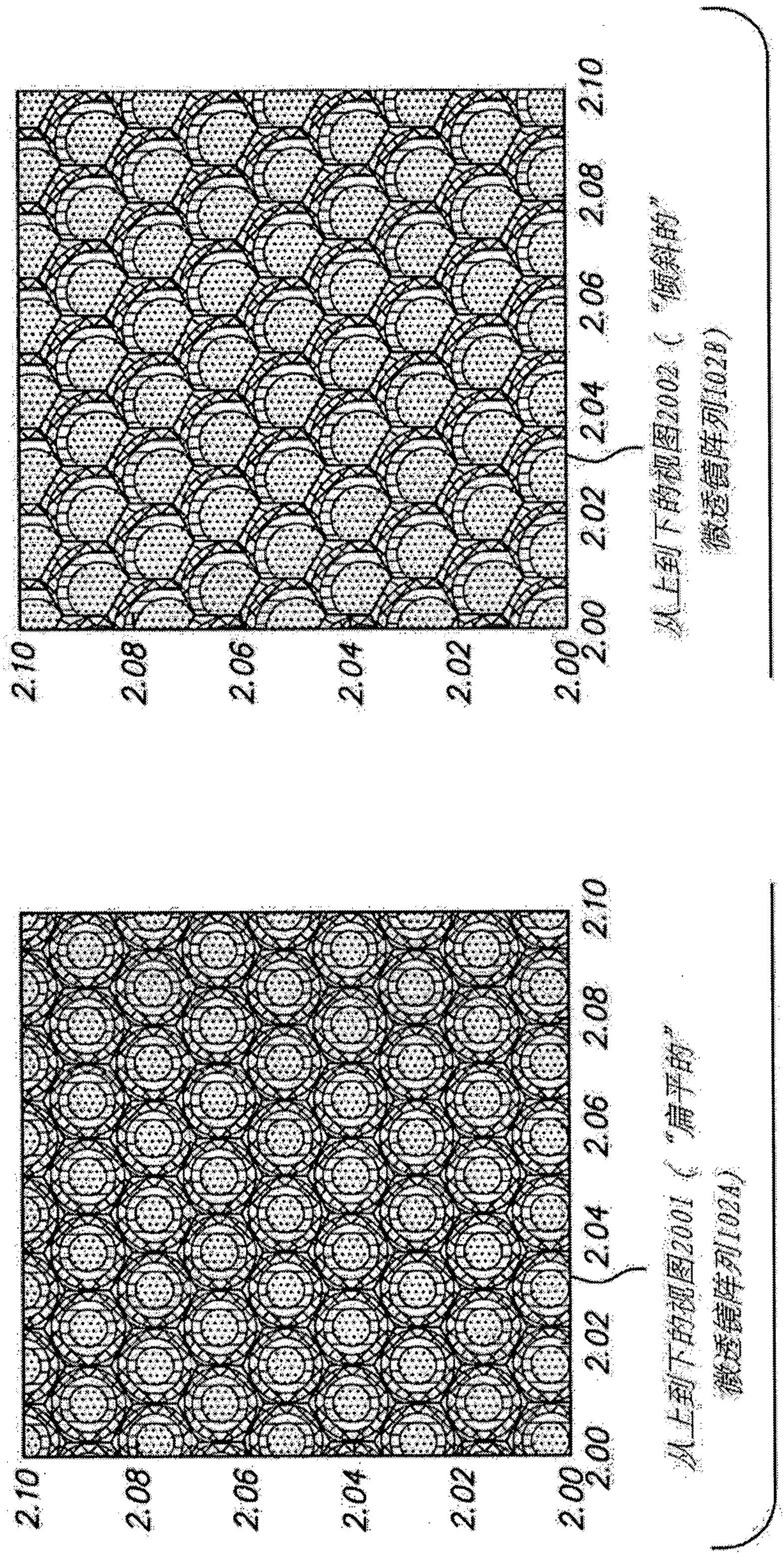
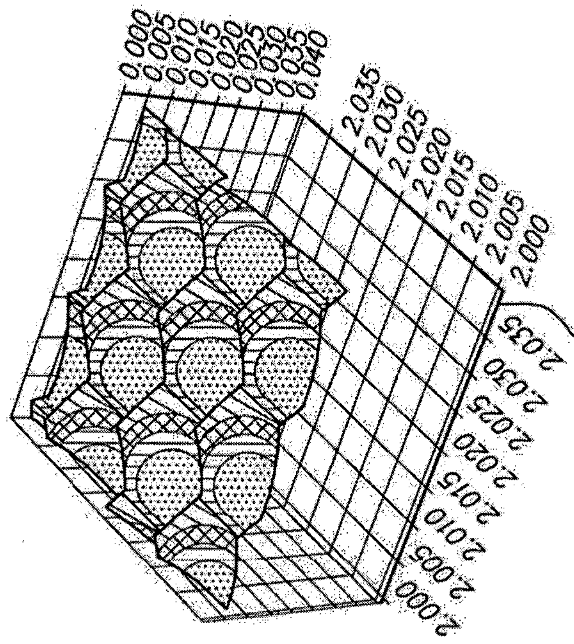
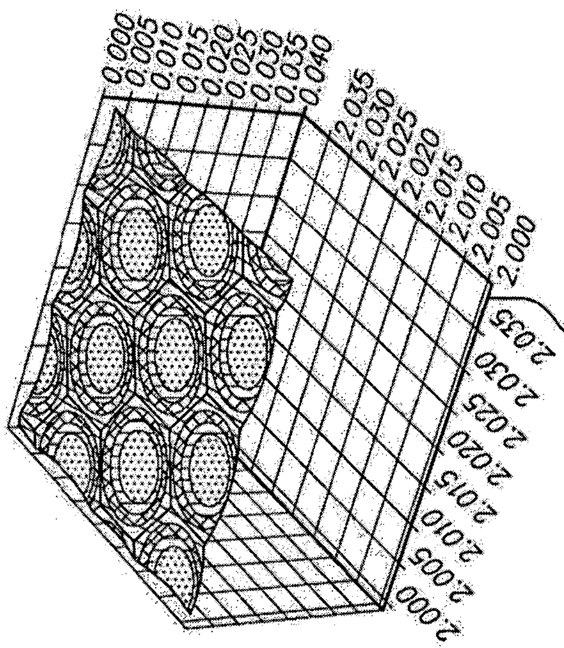

从上到下的视图2002（“倾斜的”微透镜阵列102B）
从上到下的视图2001（“扁平的”微透镜阵列102A）
2.00
2.02
2.04
2.06
2.08
2.10

图 20



3D曲线2101B（“倾斜的”微透镜阵列）



3D曲线2101A（“扁平的”微透镜阵列）

图 21

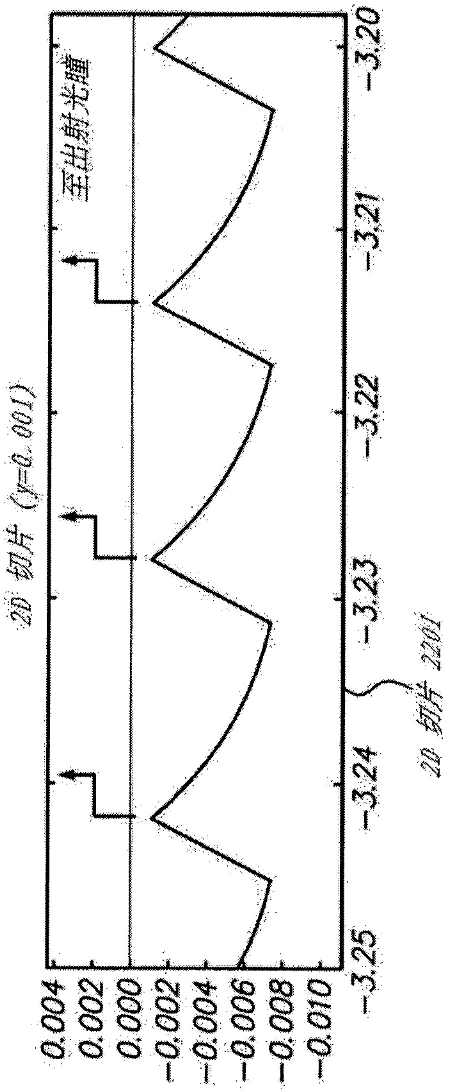

至出射光瞳
2D 切片（y=0.001）
2D 切片 2201
−3.20
−3.21
−3.22
−3.23
−3.24
−3.25
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
−0.010

图 22

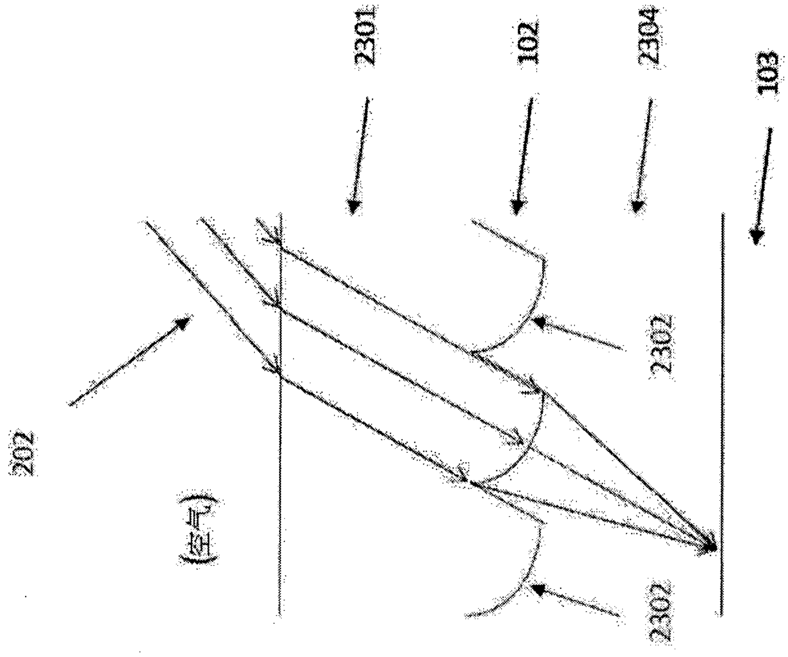


图 23A

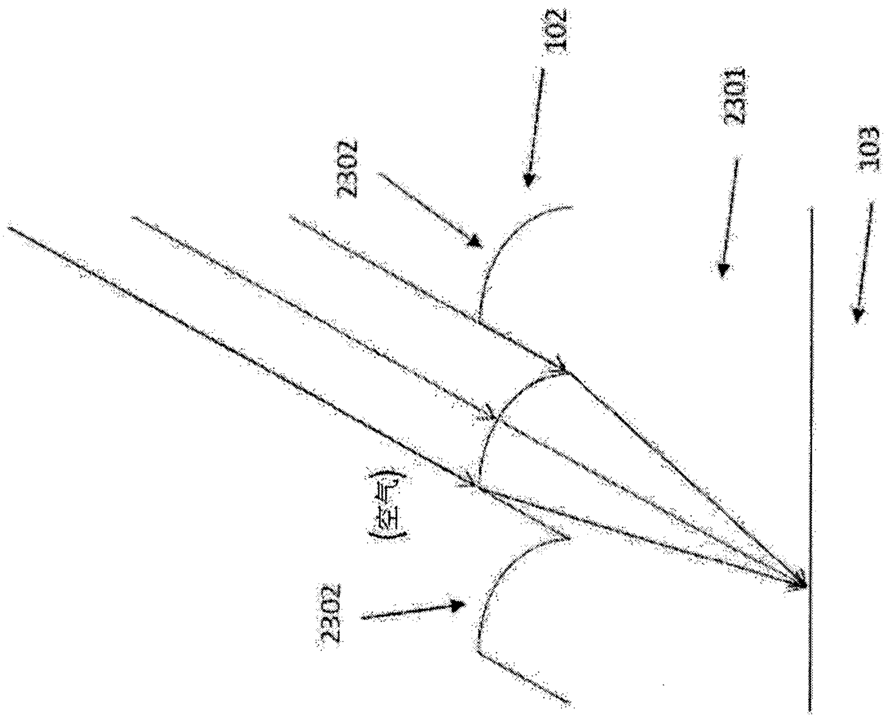


图 23B

Optimization of Optical Systems for Improved Light Field Capture and Manipulation

Abstract

According to various embodiments of the present invention, the optical systems of light field capture devices are optimized so as to improve captured light field image data. Optimizing optical systems of light field capture devices can result in captured light field image data (both still and video) that is cheaper and/or easier to process. Optical systems can be optimized to yield improved quality or resolution when using cheaper processing approaches whose computational costs fit within various processing and/or resource constraints. As such, the optical systems of light field cameras can be optimized to reduce size and/or cost and/or increase the quality of such optical systems.

用于改进的光场捕获和操作的光学系统的优化

摘要

根据本发明的各个实施例，光场捕获装置的光学系统被优化为以便改进捕获的光场图像数据。优化光场捕获装置的光学系统可以产生更加便宜和/或易于处理的捕获光场图像数据(静止的和视频)。光学系统可以被优化为在使用更加便宜的处理方法时产生改进的质量或分辨率，所述处理方法的计算成本适合各种处理和/或资源约束。因此，光场照相机的光学系统可以被优化以降低尺寸和/或成本，和/或提高这种光学系统的质量。