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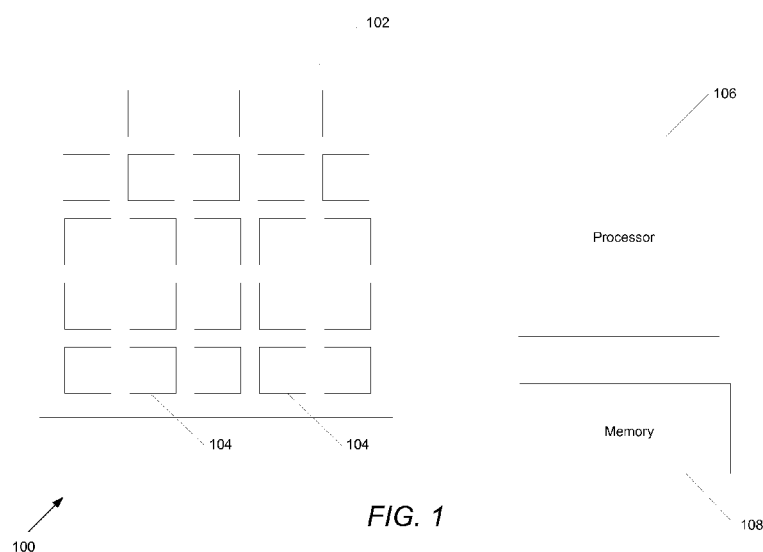


FIG. 1

(57) Abstract: Systems and methods for high dynamic range imaging using array cameras in accordance with embodiments of the invention are disclosed. In one embodiment of the invention, a method of generating a high dynamic range image using an array camera includes defining at least two subsets of active cameras, determining image capture settings for each subset of active cameras, where the image capture settings include at least two exposure settings, configuring the active cameras using the determined image capture settings for each subset, capturing image data using the active cameras, synthesizing an image for each of the at least two subset of active cameras using the captured image data, and generating a high dynamic range image using the synthesized images.

## SYSTEMS AND METHODS FOR HIGH DYNAMIC RANGE IMAGING USING ARRAY CAMERAS

### FIELD OF THE INVENTION

**[0001]** The present invention generally relates to digital cameras and more specifically to systems and methods for high dynamic range (HDR) imaging using array cameras.

### BACKGROUND

**[0002]** Current camera technology typically limits image capture possibilities to very specific conditions in which an image of acceptable quality can be produced. As a result of this limitation, several camera settings need to be appropriately chosen before an image of optimal quality can be taken. Cameras have long had the ability to assess the scene conditions and automatically adjust settings such as: exposure time, iris/lens aperture, focus, sensor gain, and the use of neutral density filters. While film-based cameras have traditionally relied on external measuring sensors to select these settings, modern compact digital cameras make use of several through-the-lens measurements that provide image-based data to automatically adjust settings through algorithms that compare these measurements and decide on optimal settings.

**[0003]** The mechanism of exposure provides adjustment of the device sensitivity to the light intensity in the scene. This is in part motivated by the limited dynamic range (ratio of highest to lowest light intensity) of the camera system compared to the dynamic range of intensities in the real world. In an imaging capture device, a metering and auto-exposure algorithm finds optimal values for the above parameters (some of these parameters may be specified or fixed). An auto-exposure algorithm aims to find the optimal exposure settings for the camera system by modifying a subset of the following parameters: exposure time, iris/lens aperture, sensor gain, and the use of neutral density filters.

**[0004]** Cameras equipped with auto-focus lens can generally capture an image of acceptable quality at a certain focus setting, while relying on an auto-focus algorithm to select the accurate focus position where the chosen parts of the image are considered to be acceptably sharp. In a traditional compact digital camera, auto-focus can be achieved by capturing successive images (or selected regions of interest in successive images) at varying focus positions through “focus sweep” and selecting the setting corresponding to the image (or selected regions of interest in the image) of best “focus”. An auto-focus algorithm aims to find the optimal focus setting for the camera system. The auto-exposure and auto-focus functions in digital cameras share the characteristic that they both generally rely on taking multiple measurements in order to estimate the best camera settings prior to actual image capture.

**[0005]** Auto-exposure algorithms may rely on external light meters/sensors or may evaluate optimal exposure time through the lens by successive image capturing as described above. In many legacy cameras auto-exposure algorithms run concurrently with image preview mode. Due to the fact that preview mode provides real time video, the auto-exposure algorithm is typically configured to make small adjustments in the exposure time since changes in exposure are immediately visible in the preview video. These small adjustments result in delays in identifying optimal exposure times.

**[0006]** Autofocus is another feature that generally runs when the device is in preview mode. Again, since image preview mode provides real time video, the autofocus process typically involves gradually varying the focus point in a slow sweep. Although there are multiple approaches to performing autofocus (including phase detection that uses dedicated focusing sensors), methods appropriate for compact cameras typically involve capturing several images and analyzing the captured images for parameters such as contrast or blur amount. Such autofocus methods, along with slow sweep, can also result in delays.

**[0007]** The High Dynamic Range (HDR) feature provides a means to produce images that convey higher dynamic range (higher ratio of intensities corresponding to light and dark areas in image). In a conventional image capture mode (i.e. one that does not involve capturing HDR information), images are traditionally captured at one exposure level (may vary for each color channel in architectures allowing this). The

camera system's dynamic range is typically limited by several factors, including the finite number of bits in the analog-to-digital converters, reduced full-well sensor capacity as well as optical characteristics. HDR mode utilizes a set of methods that sample a scene's dynamic range more aggressively by capturing multiple images of the scene at different exposure levels. Each exposure creates brackets of smaller or regular dynamic range that can be sampled to produce a composite image of high (increased) dynamic range. Various blending models and/or algorithms can be utilized to create a single HDR image from the multiple images. The High Dynamic Range mode typically includes two steps: High Dynamic Range capture and High Dynamic Range Image Blending and Compression. In the High Dynamic Range capture step, multiple images may be captured at a pre-defined difference in exposure setting from the reference exposure; for example, if the reference exposure is EV0, an image with a smaller exposure by a factor of 2 may be captured and an image with a greater exposure by a factor of 2 may be captured as following: EV0, EV-1 (short exposure), EV+1 (long exposure). (Note: numbers follow the exposure value convention and correspond to base-2 logarithmic scale such that EV-1 corresponds to half of EV0 exposure, EV+1 corresponds to double the EV0 exposure).

#### SUMMARY OF THE INVENTION

**[0008]** Systems and methods for high dynamic range imaging using array cameras in accordance with embodiments of the invention are disclosed. In one embodiment of the invention, a method of generating a high dynamic range image using an array camera includes defining at least two subsets of active cameras, determining image capture settings for each subset of active cameras, where the image capture settings include at least two exposure settings, configuring the active cameras using the determined image capture settings for each subset, capturing image data using the active cameras, synthesizing an image for each of the at least two subset of active cameras using the captured image data, and generating a high dynamic range image using the synthesized images.

**BRIEF DESCRIPTION OF THE DRAWINGS**

**[0009]** FIG. 1 is a block diagram of an array camera in accordance with an embodiment of the invention.

**[0010]** FIG. 2 conceptually illustrates an optic array and an imager array in an array camera module in accordance with an embodiment of the invention.

**[0011]** FIG. 3 is an architecture diagram of an imager array in accordance with an embodiment of the invention.

**[0012]** FIG. 4 is a high level circuit diagram of pixel control and readout circuitry for a plurality of focal planes in an imager array in accordance with an embodiment of the invention.

**[0013]** FIG. 5 is a chart that conceptually illustrates the manner in which capturing image data with specific image capture settings can result in the capture of a portion of the full dynamic range of a scene.

**[0014]** FIG. 6 is a flow chart illustrating a process for performing HDR image capture utilizing subsets of active cameras of an array camera module in accordance with an embodiment of the invention.

**[0015]** FIG. 7 conceptually illustrates a layout of color filters and the location of reference cameras within each subset of a 4 x 4 camera module in accordance with an embodiment of the invention.

**[0016]** FIG. 8 conceptually illustrates a layout of color filters and the location of reference cameras within each subset of a 4 x 4 camera module in accordance with an embodiment of the invention.

**[0017]** FIG. 9 conceptually illustrates a layout of color filters and the location of reference cameras within each subset of a 5 x 5 camera module in accordance with an embodiment of the invention.

**[0018]** FIG. 10 is a flow chart illustrating a process for determining various HDR image capture modes using a subset of active cameras in accordance with an embodiment of the invention.

**[0019]** FIGS. 11A-E conceptually illustrate applying various neutral density filters for One-shot HDR Mode in accordance with an embodiment of the invention.

## DETAILED DISCLOSURE OF THE INVENTION

**[0020]** Turning now to the drawings, systems and methods for high dynamic range (HDR) image capture using array cameras are disclosed. Array cameras including camera modules that can be utilized to capture image data from different viewpoints are disclosed in U.S. Patent Application Serial No. 12/935,504, entitled "Capturing and Processing of Images using Monolithic Camera Array with Heterogeneous Images", filed May 20, 2009, the disclosure of which is incorporated by reference herein in its entirety. In several embodiments of the invention, HDR image capture is performed by grouping subsets of active cameras in an array camera module and configuring the cameras within each subset using different image capture settings so that multiple images with different exposure settings can be synthesized using the captured image data and composited to form an HDR image. The exposure settings can be determined in a manner well known to one of ordinary skill in the art including (but not limited to) using exposure bracketing techniques. In several embodiments, one subset is configured to capture image data at low exposure levels and another subset is configured to capture image data at high exposure levels. In a number of embodiments, a so called Single Frame HDR mode and/or Multiple Frame HDR mode can be utilized to generate an HDR image based upon the depth of objects within the scene. The HDR image capture mode can be selected automatically or manually. In Single Frame HDR mode, subsets of cameras are configured using various exposure settings to capture image data over the entire dynamic range of the scene (or meaningful portion of the scene's dynamic range) in the manner discussed above. In Multiple Frame HDR mode the same set of active cameras is used to capture successive image data using different capture settings similar to traditional HDR imaging. In both the Single Frame and Multiple Frame HDR modes, the captured image data are used to synthesize high resolution images that can be composited to create an HDR image. In various embodiments, a gain-based HDR imaging mode can be utilized for various gain settings using methods including (but not limited to) those disclosed in U.S. Patent Application Serial No. 13/761,040, entitled, "Systems and Methods for Extending Dynamic Range of Imager Array by Controlling Pixel Analog Gain", filed February 6, 2013, the disclosure of which is incorporated by reference herein in its entirety. In many embodiments, a so-

called One-shot HDR mode can be utilized to achieve exposure variation among exposure pattern groups by varying transmittance while maintaining similar exposure parameters (and specific integration times) for all cameras within a specific color channel in the array. Systems and methods for performing HDR image capture in accordance with embodiments of the invention are discussed further below.

### Array Cameras

**[0021]** Array cameras in accordance with embodiments of the invention can include a camera module and a processor. An array camera in accordance with an embodiment of the invention is illustrated in FIG. 1. The array camera 100 includes a camera module 102 with an array of individual cameras 104 where an array of individual cameras refers to a plurality of cameras in a particular arrangement, such as (but not limited to) the square arrangement utilized in the illustrated embodiment. The camera module 102 is connected to the processor 106 and the processor 106 is connected to a memory 108. Although a specific array camera is illustrated in FIG. 1, any of a variety of different array camera configurations can be utilized in accordance with many different embodiments of the invention.

### Array Camera Modules

**[0022]** Camera modules in accordance with embodiments of the invention can be constructed from an imager array and an optic array. A camera module in accordance with an embodiment of the invention is illustrated in FIG. 2. The camera module 200 includes an imager array 230 including an array of focal planes 240 along with a corresponding optic array 210 including an array of lens stacks 220. Within the array of lens stacks, each lens stack 220 creates an optical channel that forms an image of the scene on an array of light sensitive pixels within a corresponding focal plane 240. Each pairing of a lens stack 220 and focal plane 240 forms a single camera 104 within the camera module. Each pixel within a focal plane 240 of a camera 104 generates image data that can be sent from the camera 104 to the processor 108. In many embodiments, the lens stack within each optical channel is configured so that pixels of each focal plane 240 sample the same object space or region within the scene. In several

embodiments, the lens stacks are configured so that the pixels that sample the same object space do so with sub-pixel offsets to provide sampling diversity that can be utilized to recover increased resolution through the use of super-resolution processes.

**[0023]** In several embodiments, color filters in individual cameras can be used to pattern the camera module with  $\pi$  filter groups as further discussed in U.S. Provisional Patent Application No. 61/641,165 entitled "Camera Modules Patterned with  $\pi$  Filter Groups" filed May 1, 2012, the disclosure of which is incorporated by reference herein in its entirety. These cameras can be used to capture data with respect to different colors, or a specific portion of the spectrum. In contrast to applying color filters to the pixels of the camera, color filters in many embodiments of the invention are included in the lens stack. For example, a green color camera can include a lens stack with a green light filter that allows green light to pass through the optical channel. In many embodiments, the pixels in each focal plane are the same and the light information captured by the pixels is differentiated by the color filters in the corresponding lens stack for each filter plane. Although a specific construction of a camera module with an optic array including color filters in the lens stacks is described above, camera modules including  $\pi$  filter groups can be implemented in a variety of ways including (but not limited to) by applying color filters to the pixels of the focal planes of the camera module similar to the manner in which color filters are applied to the pixels of a conventional color camera. In several embodiments, at least one of the cameras in the camera module can include uniform color filters applied to the pixels in its focal plane. In many embodiments, a Bayer filter pattern is applied to the pixels of one of the cameras in a camera module. In a number of embodiments, camera modules are constructed in which color filters are utilized in both the lens stacks and on the pixels of the imager array.

**[0024]** In several embodiments, an array camera generates image data from multiple focal planes and uses a processor to synthesize one or more images of a scene. In certain embodiments, the image data captured by a single focal plane in the sensor array can constitute a low resolution image (the term low resolution here is used only to contrast with higher resolution images), which the processor can use in combination with other low resolution image data captured by the camera module to construct a higher resolution image through Super Resolution processing. In many embodiments,



the image capture settings of the cameras in the array are varied to capture image data with different dynamic ranges that can be composited to form high dynamic range images.

**[0025]** Although specific array cameras are discussed above, many different array cameras are capable of utilizing  $\pi$  filter groups in accordance with embodiments of the invention. Imager arrays in accordance with embodiments of the invention are discussed further below.

#### Imager Arrays

**[0026]** An imager array in which the image capture settings of a plurality of focal planes can be independently configured in accordance with an embodiment of the invention is illustrated in FIG. 3. The imager array 300 includes a focal plane array core 302 that includes an array of focal planes 304 and all analog signal processing, pixel level control logic, signaling, and analog-to-digital conversion (ADC) circuitry. The imager array also includes focal plane timing and control circuitry 306 that is responsible for controlling the capture of image information using the pixels. In a number of embodiments, the focal plane timing and control circuitry utilizes reset and read-out signals to control the integration time of the pixels. In other embodiments, any of a variety of techniques can be utilized to control integration time of pixels and/or to capture image information using pixels. In many embodiments, the focal plane timing and control circuitry 306 provides flexibility of image information capture control, which enables features including (but not limited to) high dynamic range imaging, high speed video, and electronic image stabilization. In various embodiments, the imager array includes power management and bias generation circuitry 308. The power management and bias generation circuitry 308 provides current and voltage references to analog circuitry such as the reference voltages against which an ADC would measure the signal to be converted against. In many embodiments, the power management and bias circuitry also includes logic that turns off the current/voltage references to certain circuits when they are not in use for power saving reasons. In several embodiments, the imager array includes dark current and fixed pattern (FPN) correction circuitry 310 that increases the consistency of the black level of the image data captured by the imager

array and can reduce the appearance of row temporal noise and column fixed pattern noise. In several embodiments, each focal plane includes reference pixels for the purpose of calibrating the dark current and FPN of the focal plane and the control circuitry can keep the reference pixels active when the rest of the pixels of the focal plane are powered down in order to increase the speed with which the imager array can be powered up by reducing the need for calibration of dark current and FPN.

**[0027]** In many embodiments, a single self-contained chip imager includes focal plane framing circuitry 312 that packages the data captured from the focal planes into a container file and can prepare the captured image data for transmission. In several embodiments, the focal plane framing circuitry includes information identifying the focal plane and/or group of pixels from which the captured image data originated. In a number of embodiments, the imager array also includes an interface for transmission of captured image data to external devices. In the illustrated embodiment, the interface is a MIPI CSI 2 output interface (as specified by the non-profit MIPI Alliance, Inc.) supporting four lanes that can support read-out of video at 30 fps from the imager array and incorporating data output interface circuitry 314, interface control circuitry 316 and interface input circuitry 318. Typically, the bandwidth of each lane is optimized for the total number of pixels in the imager array and the desired frame rate. The use of various interfaces including the MIPI CSI 2 interface to transmit image data captured by an array of imagers within an imager array to an external device in accordance with embodiments of the invention is described in U.S. Patent 8,305,456, entitled "Systems and Methods for Transmitting Array Camera Data", issued November 6, 2012, the disclosure of which is incorporated by reference herein in its entirety.

**[0028]** Although specific components of an imager array architecture are discussed above with respect to FIG. 3, any of a variety of imager arrays can be constructed in accordance with embodiments of the invention that enable the capture of images of a scene at a plurality of focal planes in accordance with embodiments of the invention. Independent focal plane control that can be included in imager arrays in accordance with embodiments of the invention are discussed further below.

### Independent Focal Plane Control

**[0029]** Imager arrays in accordance with embodiments of the invention can include an array of focal planes that can independently be controlled. In this way, the image capture settings for each focal plane in an imager array can be configured differently. As is discussed further below, the ability to configure active focal planes using difference image capture settings can enable different cameras within an array camera module to capture image data at various exposure levels for creating high resolution images that can be composited to create HDR images.

**[0030]** An imager array including independent control of image capture settings and independent control of pixel readout in an array of focal planes in accordance with an embodiment of the invention is illustrated in FIG. 4. The imager array 400 includes a plurality of focal planes or pixel sub-arrays 402. Control circuitry 403, 404 provides independent control of the exposure timing and amplification gain applied to the individual pixels within each focal plane. Each focal plane 402 includes independent row timing circuitry 406, 408, and independent column readout circuitry 410, 412. In operation, the control circuitry 403, 404 determines the image capture settings of the pixels in each of the active focal planes 402. The row timing circuitry 406, 408 and the column readout circuitry 410, 412 are responsible for reading out image data from each of the pixels in the active focal planes. The image data read from the focal planes is then formatted for output using an output and control interface 416.

**[0031]** Although specific imager array configurations are discussed above with reference to FIG. 4, any of a variety of imager array configurations including independent and/or related focal plane control can be utilized in accordance with embodiments of the invention including those outlined in U.S. Patent Application Serial No. 13/106,797, entitled "Architectures for Imager Arrays and Array Cameras", filed May 12, 2011, the disclosure of which is incorporated by reference herein in its entirety. Processes for capturing HDR image data using array cameras are further discussed below.

### Capturing Image Data Using Single Frame HDR Mode

**[0032]** The dynamic range of a scene can be used to determine whether HDR imaging is appropriate. A scene's dynamic range can be measured using methods including (but not limited to) those disclosed in U.S. Provisional Patent Application Serial No. 61/775,395, entitled, "Systems and Methods for Measuring Scene Information while Capture Image Data", filed March 8, 2013, the disclosure of which is incorporated by reference herein in its entirety. Many times, the dynamic range of a camera module can capture the entire dynamic range of the scene and/or a portion of the dynamic range determined to be useful. In such situations, a standard capture mode (non HDR mode) where the same image capture settings can be utilized for the cameras in each color channel can be used to capture the full dynamic range of the scene. However, as illustrated in FIG. 5, the dynamic range of a scene 502 can be much greater than the dynamic range of a single camera in an array camera module 506. The difference in dynamic ranges creates a so called clipping affect at the outer limits of the camera's dynamic range 504, 508. The regions of the scene's dynamic range that are outside the camera module's dynamic range 506 are either underexposed or overexposed and thus image data is not accurately captured. Exposure times can be adjusted at multiple iterations to identify the exposure settings that best satisfy a set of predetermined criteria and/or to capture image data over the entire dynamic range of the scene for the purposes of HDR imaging. In various embodiments, optimal exposure settings may be determined using an iterative process. Processes for performing HDR image capture using subsets of active cameras within an array camera module in accordance with embodiments of the invention are discussed further below.

**[0033]** A process for performing HDR image capture utilizing subsets of active cameras within an array camera module in accordance with an embodiment of the invention is illustrated in FIG. 6. The process 600 includes capturing (602) image data using the active cameras of the camera module as discussed above. The captured image data can be analyzed to determine (604) the dynamic range of the scene. In order to decide whether to utilize the so called Single Frame HDR mode to capture image data using subsets of cameras configured at various settings, a determination

(606) is made as to whether the dynamic range in the scene exceeds a predetermined threshold. In many embodiments of the invention, the threshold can be a function of the dynamic range of the camera module implemented in the imager array. If the dynamic range in the scene does not exceed the predetermined threshold value, a standard capture mode (non-HDR mode) is utilized to capture image data where the cameras in each color channel use the same image capture settings (616) and an image is synthesized (618) using the captured image data. If the dynamic range of the scene exceeds the threshold value, subsets of active cameras of a camera module can be determined (608) for use in HDR image capture as further described below. In various embodiments, the exposure settings can be determined in a manner well known to one of ordinary skill in the art including (but not limited to) selecting (610) dynamic range bracketing for the purpose of high dynamic range capture. For each subset of cameras, various exposure settings are determined (612) for capturing HDR image data. The exposure settings are used to configure (614) each subset of cameras of the camera module to capture image data at various exposure levels. The active cameras of each subset of cameras capture (616) image data at their respective exposure settings and an image can be synthesized (618) for each subset from the captured image data.

**[0034]** Although specific processes for performing HDR image capture using subsets of active cameras are discussed above with respect to FIG. 6, any of a variety of processes for performing HDR image capture using subsets of active cameras can be utilized as appropriate to the requirements of a specific application in accordance with embodiments of the invention. Capturing image data using subsets of active cameras for HDR image capture in accordance with embodiments of the invention are discussed further below.

#### Selecting Subsets of Active Cameras for use in HDR Image Capture

**[0035]** Active cameras in an array camera module in accordance with embodiments of the invention can be arranged into subsets and configured using various exposure settings to capture HDR image data that can be utilized to synthesize images. The ability to synthesize images can be enhanced by the selection of cameras in each subset. In many embodiments, the subsets are defined so that red (R) and blue (B)

color information are symmetrically disposed about the green reference camera. Thus in a 2 dimensional array the red and blue color information should be available above, and below and left, and right of a green (G) reference camera, while in a linear array the red and blue color information is available to the left and right of the green reference color. In some embodiments, one could also have near-IR spectral color symmetrically disposed around the green reference camera. A camera module including a first subset of active cameras and a second set of active cameras configured to capture image data at various exposure levels in accordance with embodiments of the invention is illustrated in FIG. 7. The 4 x 4 array camera module 700 includes a first subset 702 of 8 active cameras including a green camera at the top left, top right, and bottom left corners, a green reference camera indicated by a box 704, blue cameras above and below the reference camera, and red cameras to the left and right sides of the reference camera. In several embodiments, the locations of the red and blue cameras within the first subset 702 are swapped and/or an alternative collection of cameras can be utilized. The array camera module 700 includes a second subset 706 of 8 active cameras including a row of blue, green, and red cameras placed below the first subset 702 and a column of red, green, and blue cameras placed to the right side of the first subset with a green camera connecting the row and the column and a green reference camera indicated by a box 708.

**[0036]** Depending on factors including (but not limited to) object location and light intensities within a scene, various arrangements of active cameras of a camera module into subsets can be determined. A camera module including a first subset of active cameras and a second subset of active cameras configured to capture image data at various exposure levels in accordance with embodiments of the invention is illustrated in FIG. 8. The 4 x 4 array camera module 800 is camera module 700 (FIG. 7) reflected along a diagonal axis and includes a first subset 802 of 8 active cameras including a green reference camera indicated by a box 804, a green camera at the top left corner with a row of red, green, and blue cameras to the right and a column of blue, green, and red cameras below. The camera module 800 includes a second subset 806 of 8 active cameras including a green camera at the bottom right, bottom left, and top right corners, a green reference camera indicated by a box 808, and red cameras above and below

the reference camera, and blue cameras to the right and left of the reference camera. In several embodiments, the locations of the red and blue cameras within the subset 806 are swapped and/or an alternative collection of cameras can be utilized. In some embodiments, a subset of active cameras is configured to capture image data in conjunction with a flash that is triggered to illuminate the scene. The flash could have a spectral profile that is in the visible range of wavelengths for cameras in the subset that are sensitive to visible light. In other embodiments, the flash could have a spectral profile in the near-IR range for cameras that are near-IR sensitive.

**[0037]** As discussed above, various arrangements and collections of active cameras can be utilized in any of a variety of different array camera modules including array camera modules having any of a variety of number and/or arrangement of cameras in accordance with embodiments of the invention. A 5 x 5 array camera module including a first subset of active cameras and a second subset of active cameras, where each subset is configured to capture image data at various exposure levels in accordance with embodiments of the invention is illustrated in FIG. 9. The 5 x 5 camera module 900 includes a first subset of 13 active cameras denoted by the color of the camera and subscripted with the number 1 902. The first subset includes a top row comprising two green cameras with one at the center and the other at the far right corner; a second row comprising a blue, green, and red cameras positioned adjacent to each other starting with the blue camera from the far left side; a third row comprising a green center reference camera indicated by a box 904 and blue camera directly to the right of the reference camera 904; a fourth row comprising a red camera on the far left and a green camera one position from the far right; and a fifth row comprising a green, blue, green, and red cameras positioned adjacent to each other starting with the green camera from the far left corner. The camera module 900 includes a second subset of 12 active cameras denoted by the color of the camera subscripted with the number 2 906. The second subset includes a top row comprising a green camera at the top left corner, a red camera adjacent and to the right of the green camera, and a blue camera two positions to the right of the red camera; a second row comprising a red camera at the far right and a green camera adjacent and to the left the red camera; a third row comprising a green camera to the far left, a blue camera adjacent and to the right of the

green camera, and another green camera at the far right; a fourth row comprising a red camera below the green reference camera 904, a green camera directly to the left of it, and a blue camera to the far right; and a fifth row comprising a green camera at the far right corner.

**[0038]** Although all of the cameras in the array camera modules illustrated in FIGS. 7, 8, and 9 are shown as capturing image data, in many embodiments one or more of the cameras within the array camera modules of FIGS. 7, 8, and 9 can be idle during image capture to conserve power as appropriate to the requirements of a specific application. Furthermore, the subsets need not contain the same number of cameras. In many embodiments, the cameras in an array camera module are configured into subsets having different numbers of cameras in order to perform HDR image capture.

**[0039]** Although specific arrangements of active cameras into a first, second and/or third subsets of active cameras of a camera module are discussed above with respect to FIGS. 7, 8, and 9, various camera module sizes and any of a variety of arrangements of active cameras into subsets of active cameras in camera modules can be utilized as appropriate to the requirements of a specific application in accordance with an embodiment of the invention. Processes for capturing image data at various exposure levels in consideration of objects within the scene are further described below.

#### Capturing Image Data Using Single Frame and/or Multiple Frame HDR Modes

**[0040]** Disparity increases the closer an object is to the cameras in an array camera module. When a smaller number of cameras capture image data, the likelihood that artifacts will be created near depth discontinuities in an image synthesized using the color data is increased due to the presence of occlusions. The likelihood that such artifacts will be present is highest when an object is close to the cameras and the disparity between the object in the captured images is greatest due to the fact that occlusion areas are largest. For scenes containing objects only at far distances and when using arrays with a limited number of cameras, single frame HDR mode may be utilized. At these distances, the likelihood of incurring significant occlusion artifacts is very small. In many embodiments of the invention, if an object within a scene is within a predetermined distance from the array camera module, then Multiple Frame HDR mode



is utilized. The Multiple Frame HDR mode functions similar to traditional HDR imaging, where the same set of active cameras is used to capture successive image data using different capture settings. The sets of image data are used to synthesize high resolution images that are then composited to create an HDR image. The benefit of configuring the active cameras to capture successive set of image data using different image capture settings is that more cameras can be utilized relative to the Single Frame HDR mode and the likelihood of artifacts is reduced. If the object within the scene is a sufficient distance away, then Single Frame HDR mode can be utilized as described above. The threshold distance can be determined based on the camera array specification and depends on baseline between furthest cameras, focal length and the sensor pixel pitch using the general stereo disparity formula:  $\text{disparity [in pixels]} = \text{baseline} * \text{focal length} / (\text{distance} * \text{pixel\_pitch})$ . In some embodiments, the threshold distance is computed such that the disparity between these furthest cameras is below 1 pixel such that the potential occlusion artifacts are minimized.

**[0041]** A process for performing HDR image capture using subsets an array camera in a manner that adapts based upon scene object distance in accordance with an embodiment of the invention is illustrated in FIG. 10. The process 1000 includes capturing image data using one or more active cameras. The image data can be optionally used to synthesize an image and generate (1002) a preview of the synthesized image. The synthesized image and/or captured image data is analyzed to estimate (1004) the dynamic range of the scene. In many embodiments, a determination is made (1006) as to whether the dynamic range of the scene exceeds a predetermined threshold. If the dynamic range of the scene does not exceed the predetermined threshold, HDR imaging is not utilized and image data is captured using a standard (non-HDR) image capture mode (1016). If the dynamic range in the scene does exceed a threshold value, then a depth map is generated (1008) based upon the preview and/or the captured image data. In various embodiments, the depth map can be generated using methods including (but not limited to) techniques disclosed in in U.S. Provisional Patent Application Serial No. 61/691,666, entitled, "Systems and Methods for Parallax Detection and Correction in Images Captured Using Array Cameras" filed August 21, 2012, the disclosure of which is incorporated by reference

herein in its entirety. In several embodiments, the depth map is evaluated to determine (1010) if an object is within a predetermined threshold distance from the array camera module. If the objects are within the threshold distance, then Multiple Frame HDR imaging mode is utilized (1012) to capture image data as described above. If the objects are not within the threshold distance, then Single Frame HDR imaging mode is utilized (1014) to capture image data as described above. In various embodiments, One-shot HDR imaging mode can be utilized to achieve exposure variation among exposure pattern groups of active cameras of an array while maintaining similar exposure parameters for all cameras within a specific color channel in the array as further discussed below.

**[0042]** Although specific processes for performing HDR imaging using subsets of active cameras in consideration of object distance are discussed above with respect to FIG. 10, any of a variety of processes for performing HDR imaging using subsets of active cameras in consideration of scene object distance can be utilized as appropriate to the requirements of a specific application in accordance with an embodiment of the invention. Capturing image data using One-shot HDR Mode imaging in accordance with embodiments of the invention are discussed further below.

#### One-shot (same-exposure) HDR Mode Imaging

**[0043]** As discussed above, HDR imaging can be achieved in an array camera by independently controlling exposure for various subsets of active cameras. Typically, when a particular subset of cameras are exposed differently than the cameras in a main exposure subset, a trade-off is made between spatial resolution in the main exposure for increased dynamic range (effectively increasing exposure sampling at the expense of decreased spatial sampling at the main exposure). However, in some systems and/or applications, it may be beneficial for all active cameras in the array to share the same exposure parameters (such as but not limited to systems where super-resolution processes are performed).

**[0044]** In many embodiments, a so-called One-shot HDR mode can be utilized to achieve exposure variation among subsets of active cameras (exposure pattern groups) while maintaining similar exposure parameters (and specific integration times) for all cameras in the array. Such exposure variation can be achieved by varying transmittance from one exposure pattern groups to another. The One-shot HDR mode can be implemented utilizing filters including (but not limited to) color and/or neutral density filters. In several embodiments, color filters can be stacked or the thickness of a filter layer varied to allow for desired transmittance. In other embodiments, the transmittance of either individual cameras or a camera group may be controlled by an LCD placed in the optical path.

**[0045]** Exposure pattern groups can be determined by selecting a subset of active cameras and applying the color and/or neutral density filters to the subset. In many embodiments, neutral density filters corresponding to the exposure pattern group may be permanently applied in the optical path in front of a lens, between different lens elements and/or between the lens and the sensor or even lithographically deposited on the lens, sensor or additional glass carriers. In other embodiments, neutral density filters corresponding to desired exposure pattern groups may be inserted, on demand, in the optical path. Further, neutral density filters can be part of the camera array module internally and may be controlled mechanically and/or electronically or attached externally on top of the camera array module by the user whenever One-shot HDR mode is desired.

**[0046]** In many embodiments, the neutral density filters can be individual filters that are applied to each individual active camera or a single array filter that can be applied to all cameras of an exposure pattern group. Conceptual illustrations for applying various neutral density filters for desired exposure pattern groups in accordance with an embodiment of the invention is shown in FIGS. 11A-E. Application of individual neutral density filters for One-shot HDR mode in accordance with an embodiment of the invention is shown in FIGS. 11A-B. When One-shot HDR mode is not enabled 1100, the neutral density filters 1104 do not cover the optical paths of the lens 1102. However, when One-shot HDR mode is enabled 1110, the neutral density filters are placed in the

optical path 1112. The desired exposure pattern group can be created by placing one or more individual filters (as indicated by the shaded regions).

**[0047]** In some embodiments, particularly where the desired exposure pattern group represents cameras clustered close together, a single array neutral density filter can be used. Application of an array neutral density filter for One-shot HDR mode in accordance with an embodiment of the invention is shown in FIG. 11C. When One-shot HDR mode is enabled 1120, a single array filter 1122 creates the desired exposure group. In several embodiments, a single neutral density filter can be applied using a rotating wheel mechanism. Application of array neutral density filters utilizing a rotational mechanism for One-shot HDR mode in accordance with embodiments of the invention are shown in FIGS. 11D-E. When One-shot HDR mode is enabled 1130, the array filter 1132 covers the optical paths for the exposure pattern group. When One-shot HDR mode is not enabled, a rotational mechanism 1134 removes the array filter. In various embodiments, the rotational mechanism 1146 can provide for several exposure group patterns corresponding to different positions along the rotational path. In one position, an array filter 1142 can cover one exposure pattern group. Upon rotation, another filter 1144 can create a different exposure pattern group. Further, the rotational mechanism can also provide for not applying any filter at all. As discussed above, the shape and size of the neural density filters can vary along with the specific method of implementation. Although specific neutral density filters and their application to an array camera for enabling One-shot HDR mode are discussed above with respect to FIGS. 11A-E, any of a variety of filters and applications to array cameras as appropriate to the requirements of the a specific application can be utilized in accordance with embodiments of the invention.

**[0048]** While the above description contains many specific embodiments of the invention, these should not be construed as limitations on the scope of the invention, but rather as an example of one embodiment thereof. It is therefore to be understood that the present invention may be practiced otherwise than specifically described, without departing from the scope and spirit of the present invention. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive.

## WHAT IS CLAIMED IS:

1. A method of generating a high dynamic range image using an array camera, the method comprising:
  - defining at least two subsets of active cameras;
  - determining image capture settings for each subset of active cameras, where the image capture settings include at least two exposure settings;
  - configuring the active cameras using the determined image capture settings for each subset;
  - capturing image data using the active cameras;
  - synthesizing an image for each of the at least two subset of active cameras using the captured image data; and
  - generating a high dynamic range image using the synthesized images.

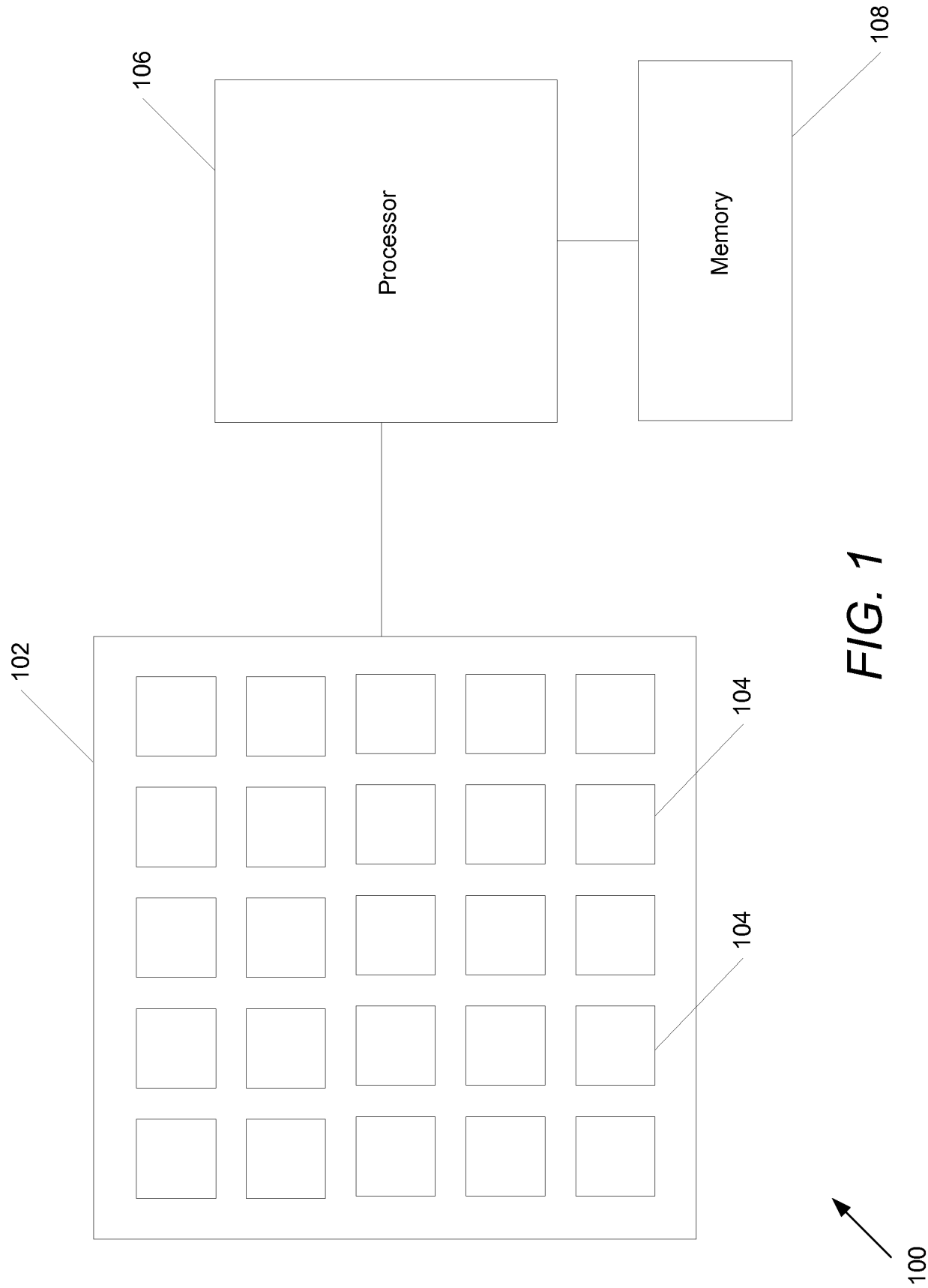


FIG. 1

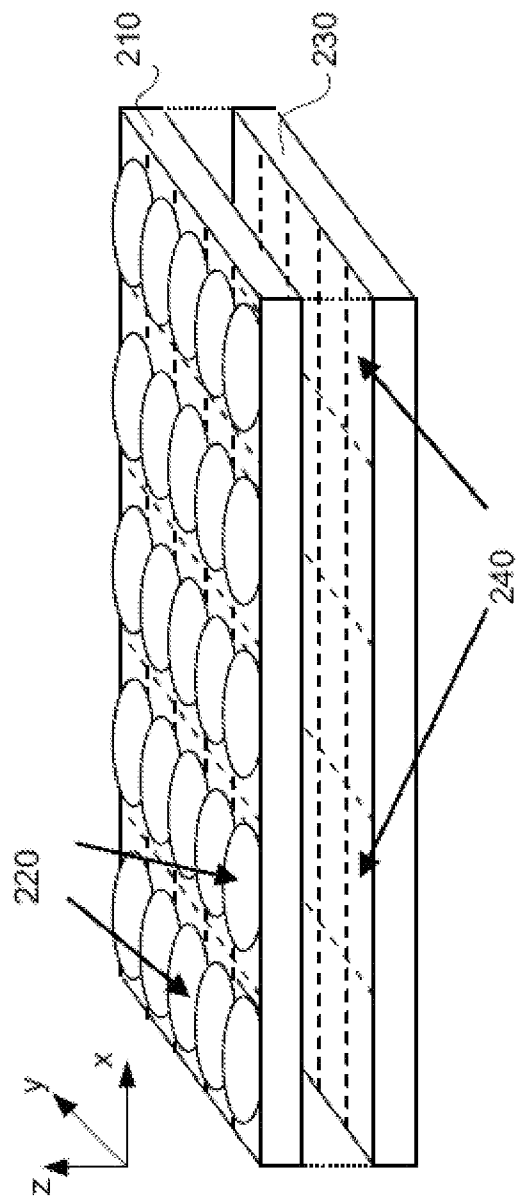


FIG. 2

200

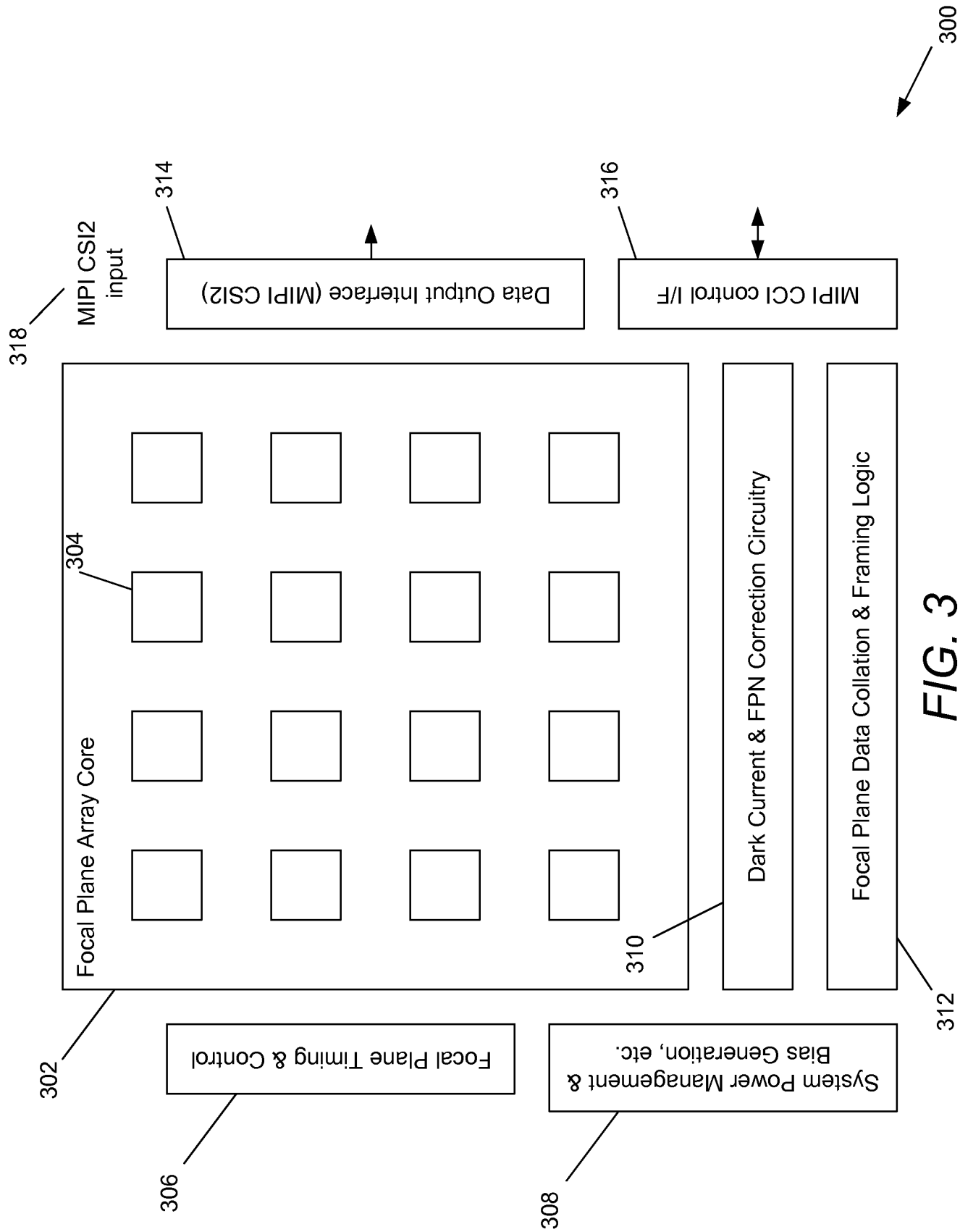
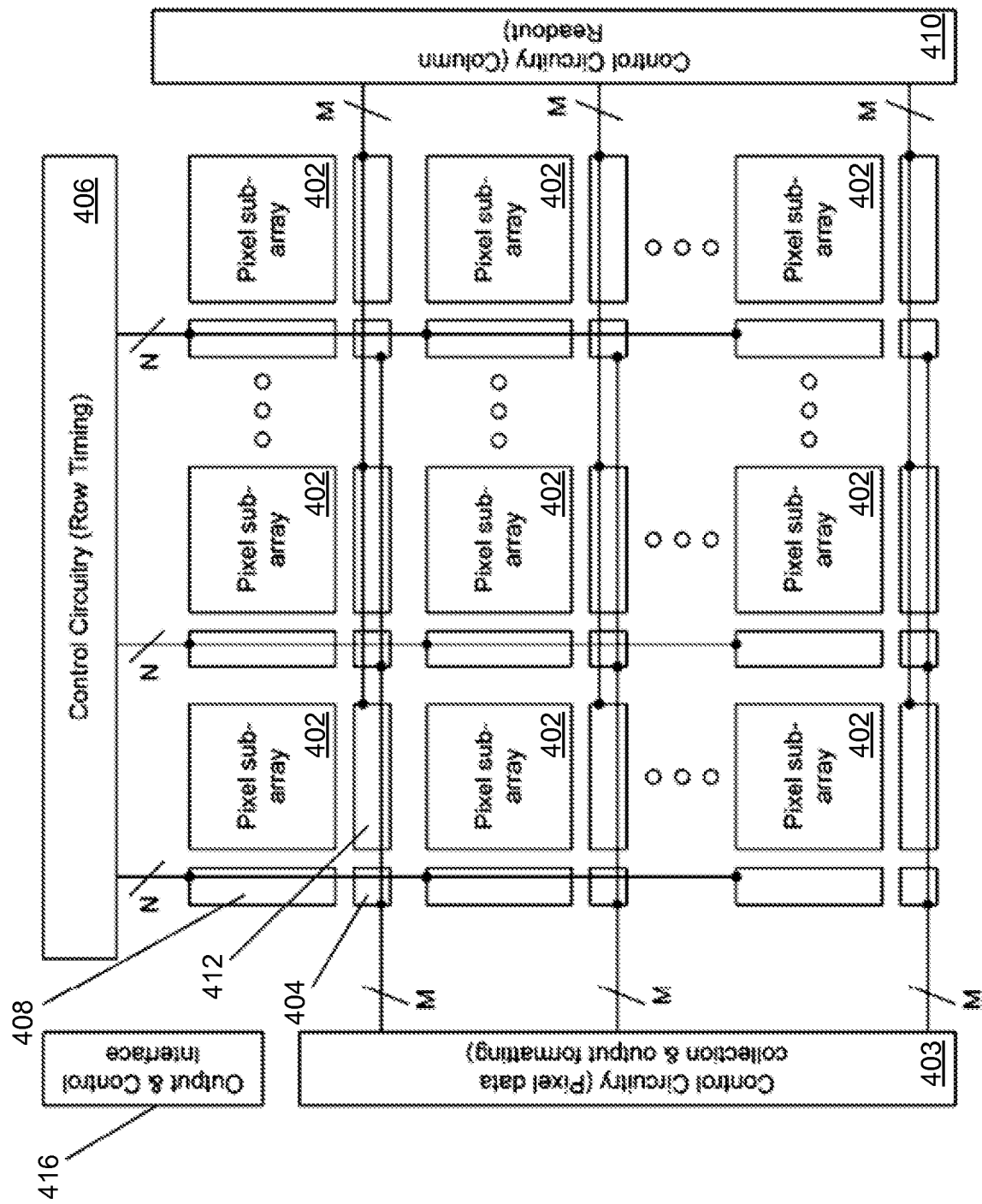


FIG. 3





**FIG. 4**

400

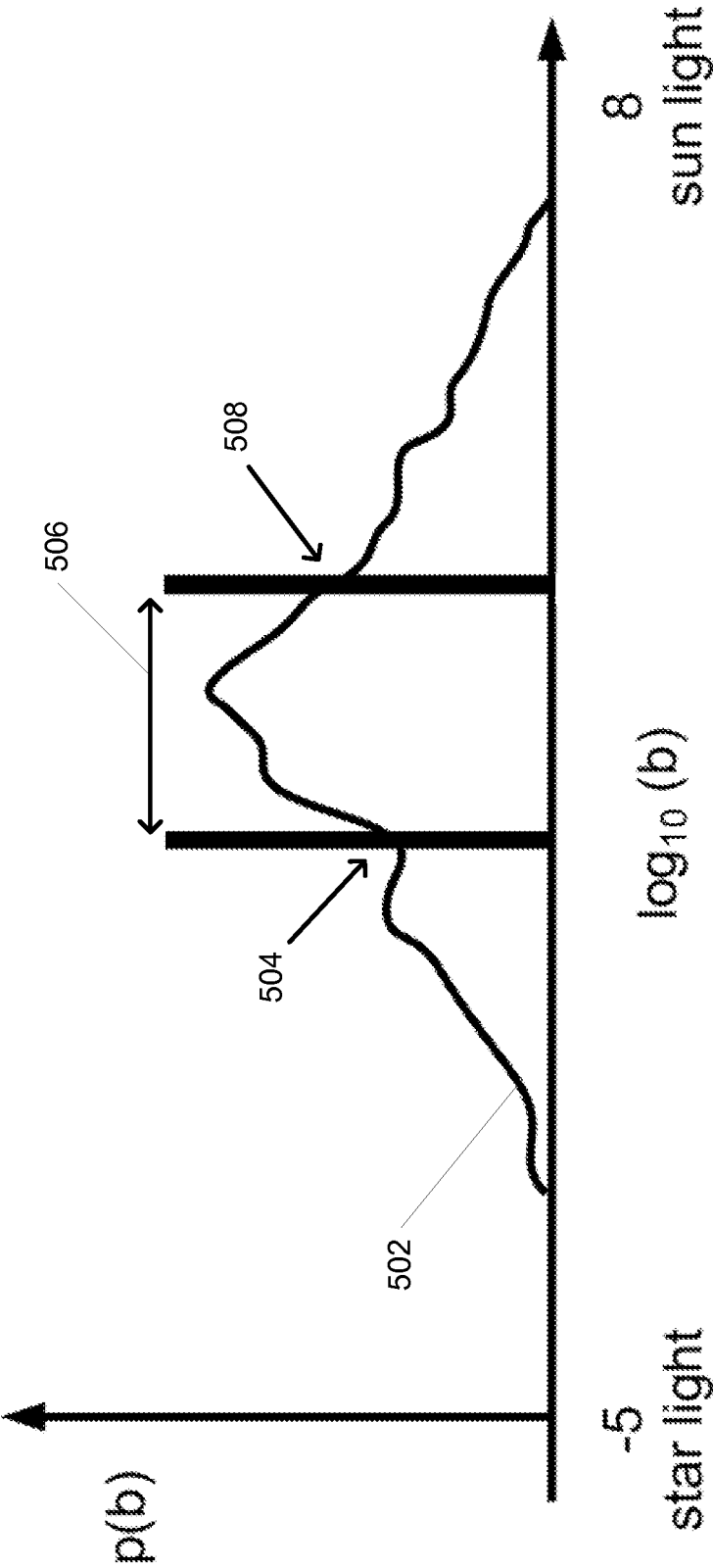


FIG. 5

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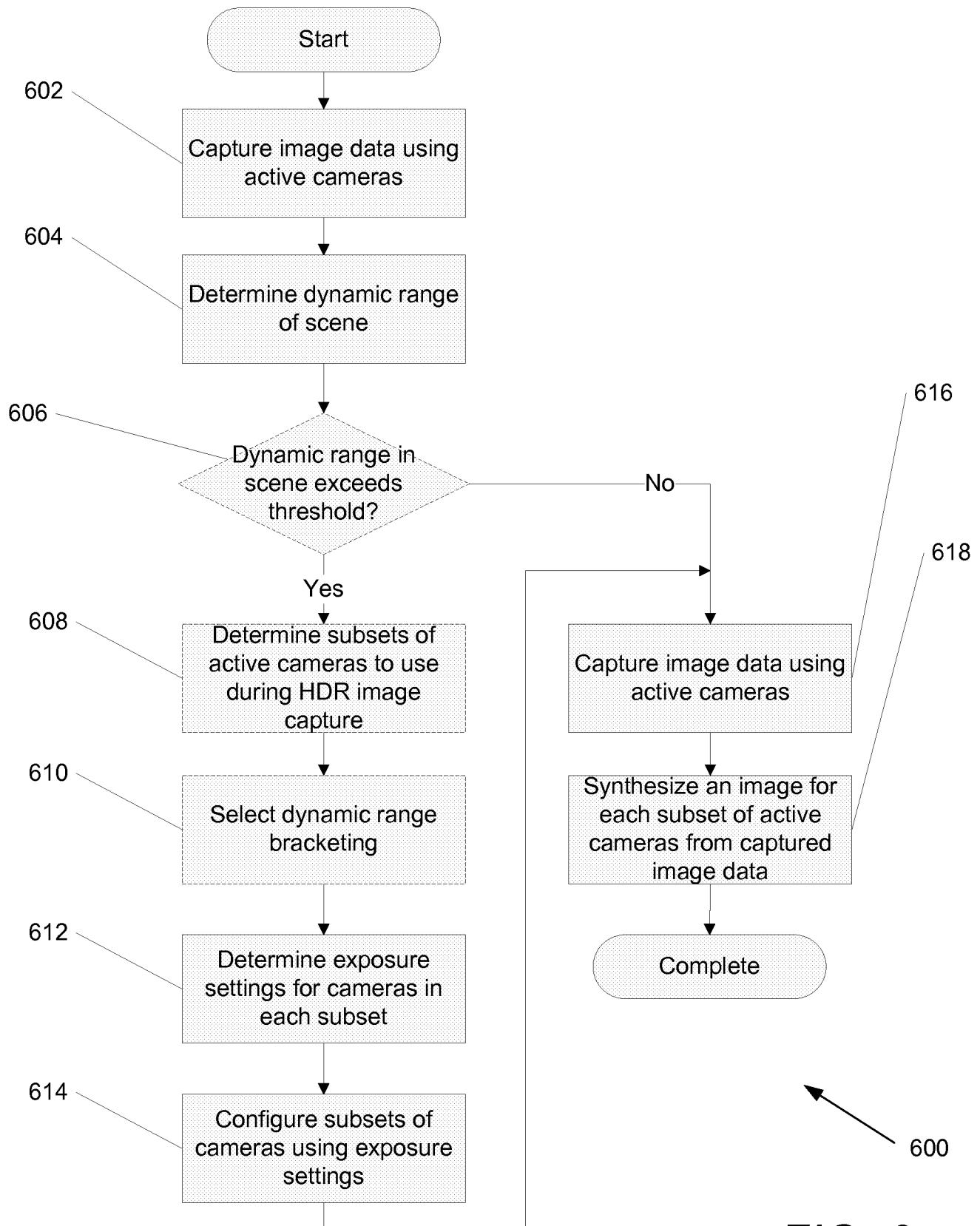


FIG. 6

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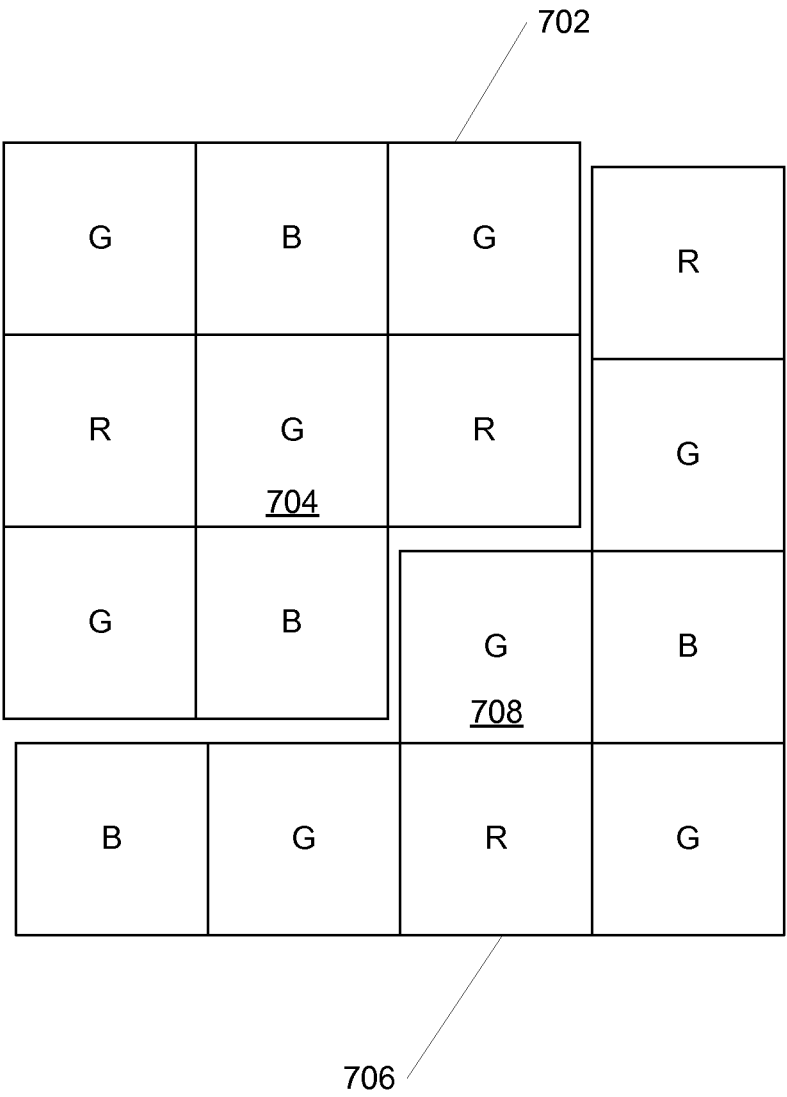


FIG. 7

700 ↗

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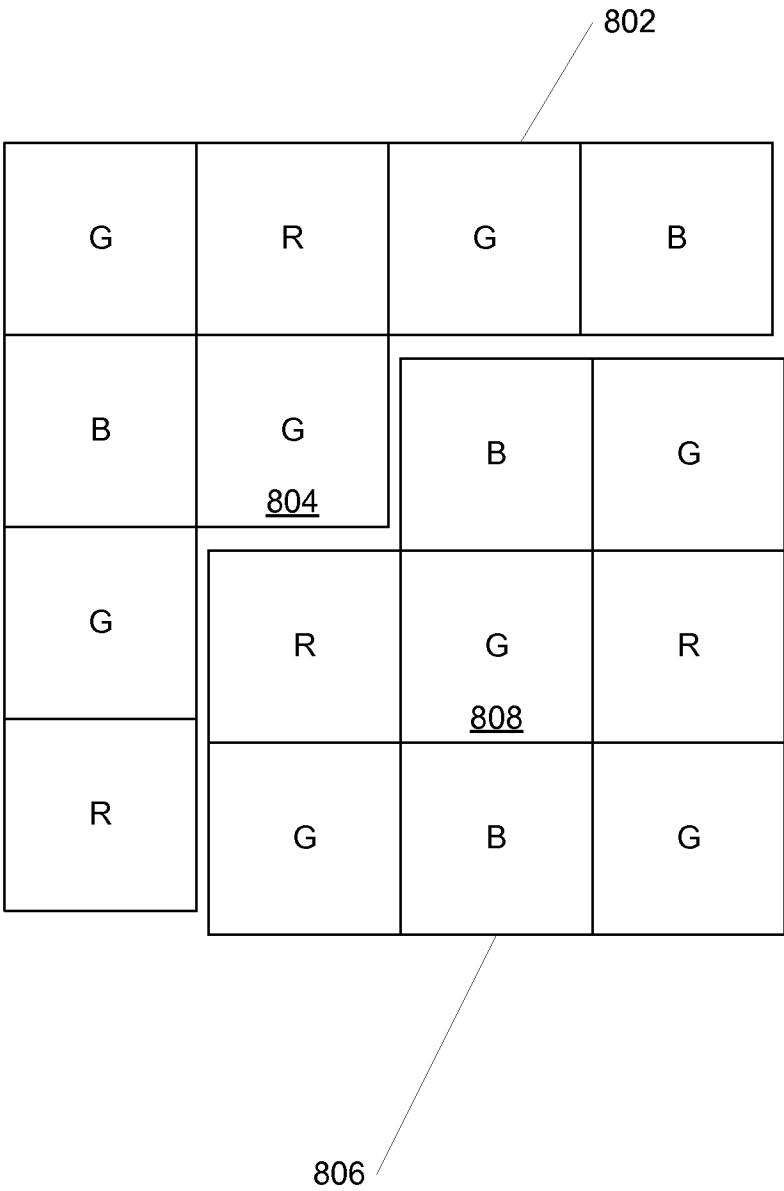


FIG. 8

800

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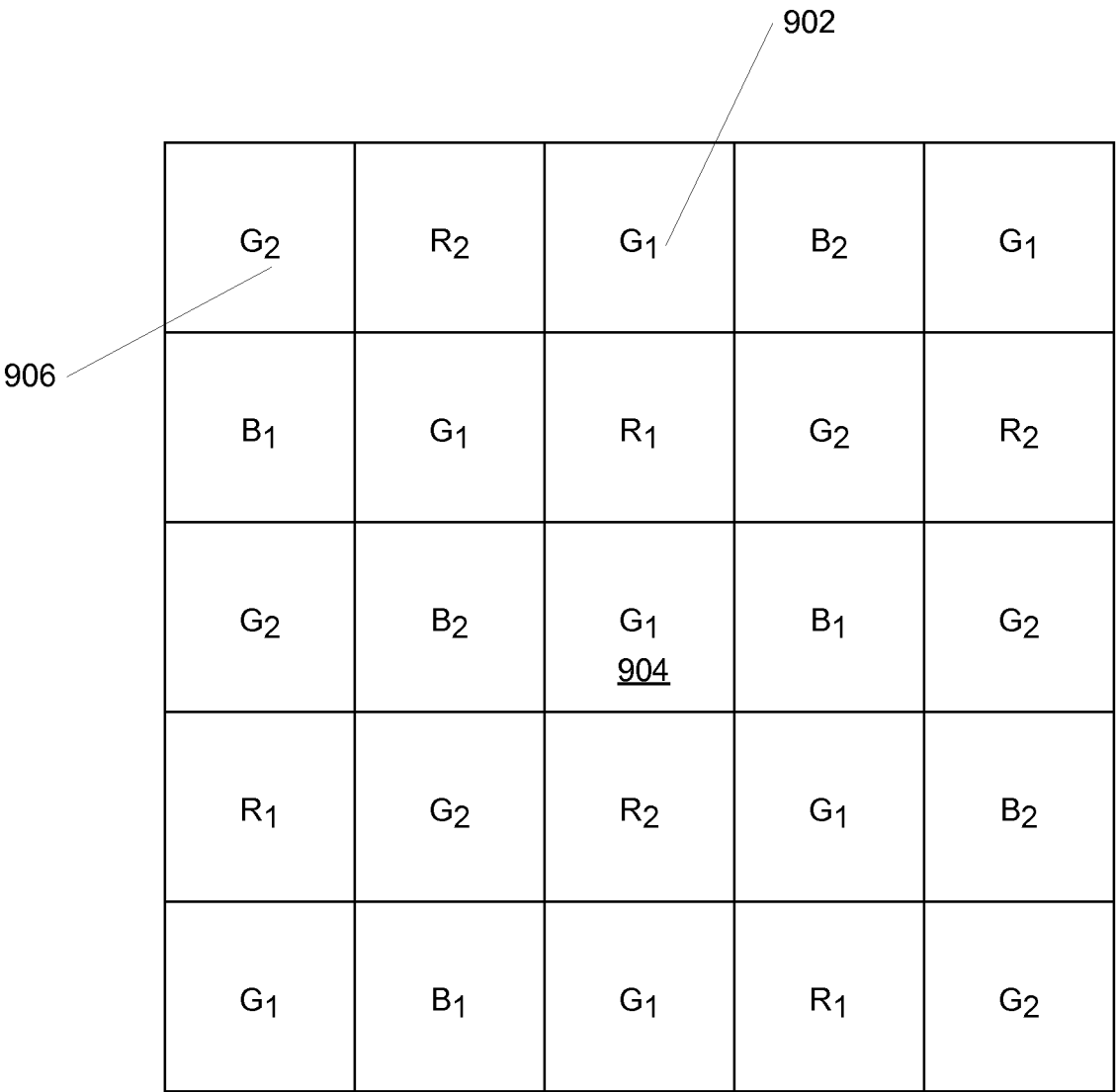


FIG. 9

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Start

Generate preview using a  
subset of active cameras

Estimate dynamic range  
in scene

Dynamic range in  
scene exceeds  
threshold?

Yes

Generate depth map  
based upon preview

Objects within  
threshold distance?

No

Standard Image Capture

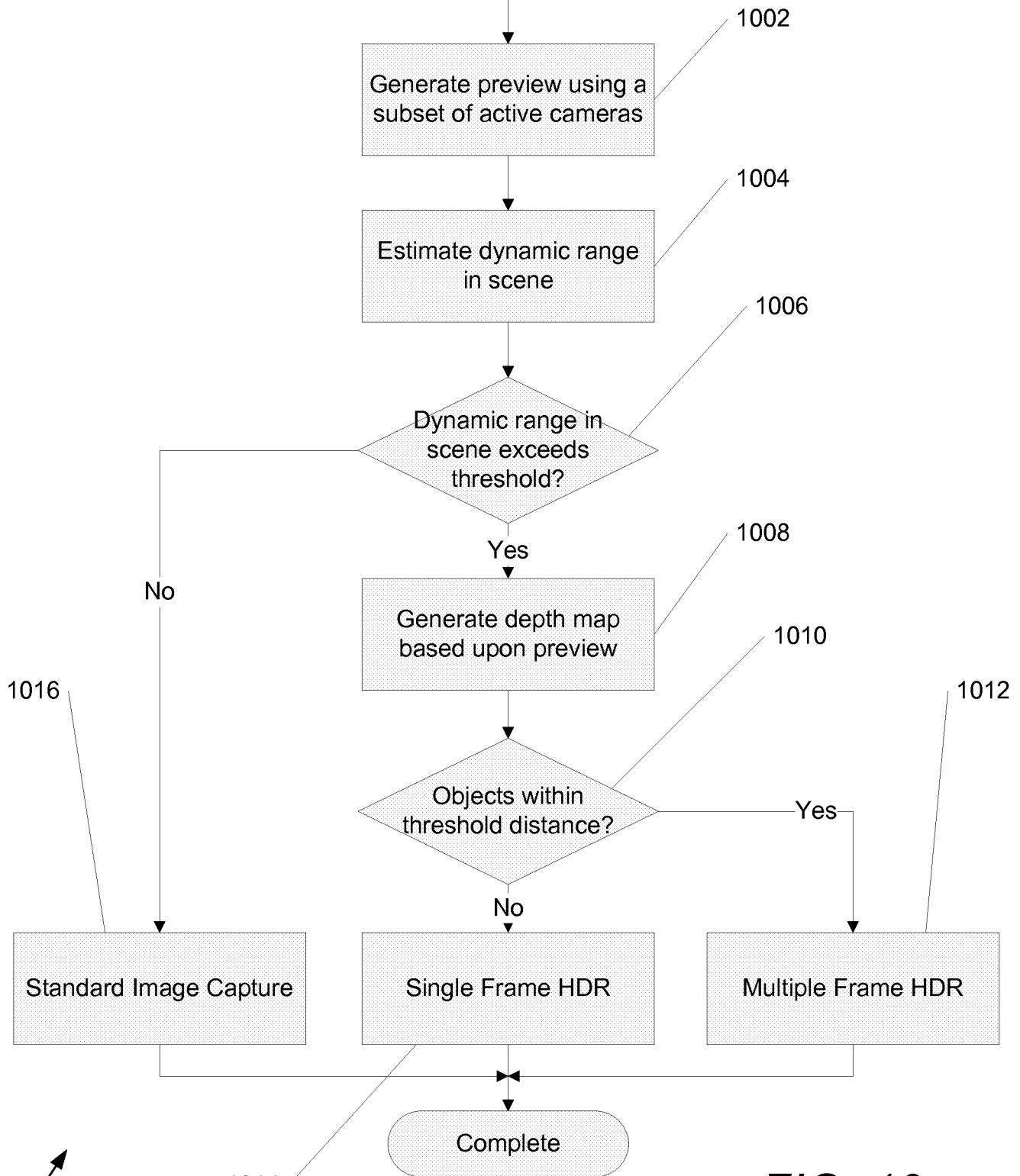
Single Frame HDR

Multiple Frame HDR

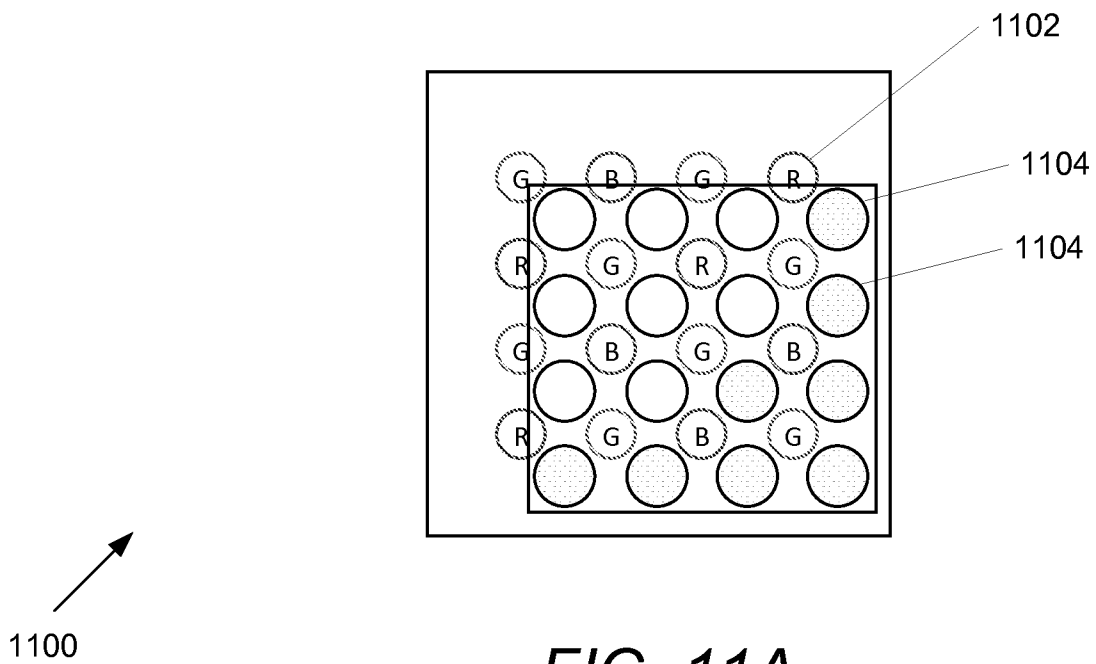
Complete

1000

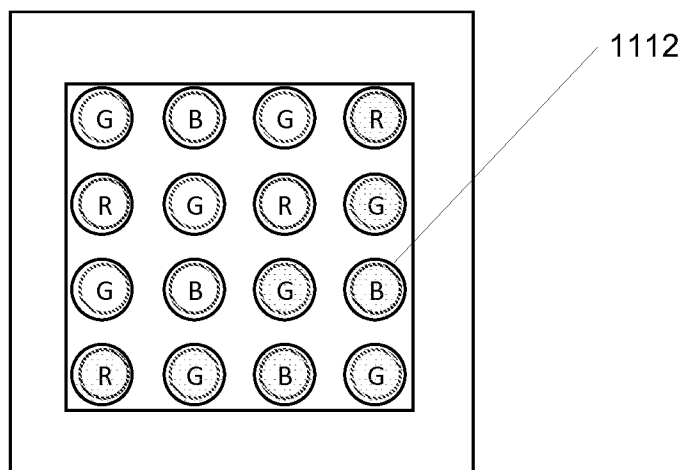
FIG. 10



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**FIG. 11A**

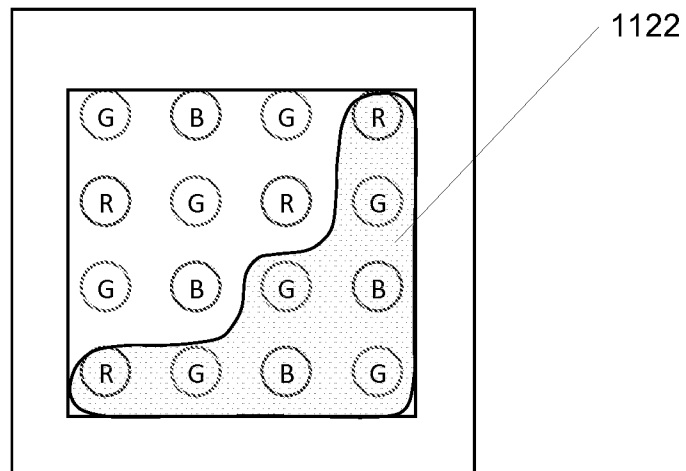


**FIG. 11B**

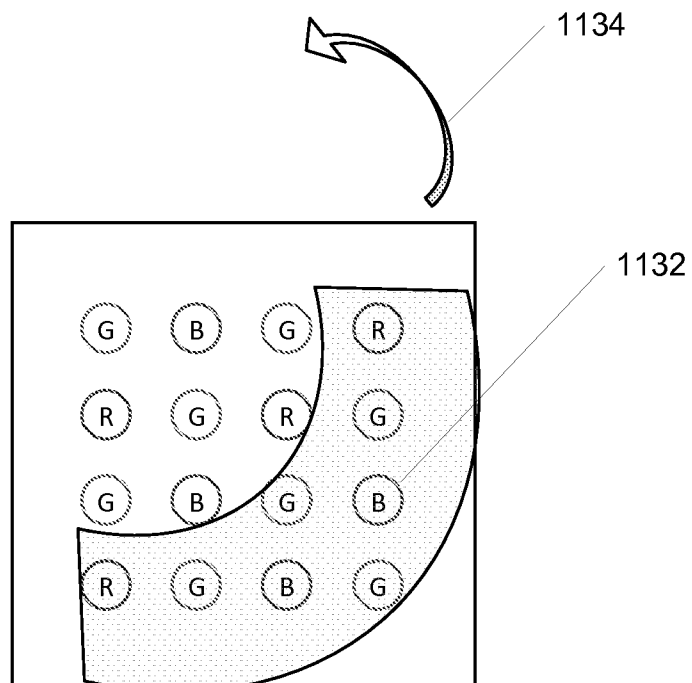
1110



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**FIG. 11C**



**FIG. 11D**

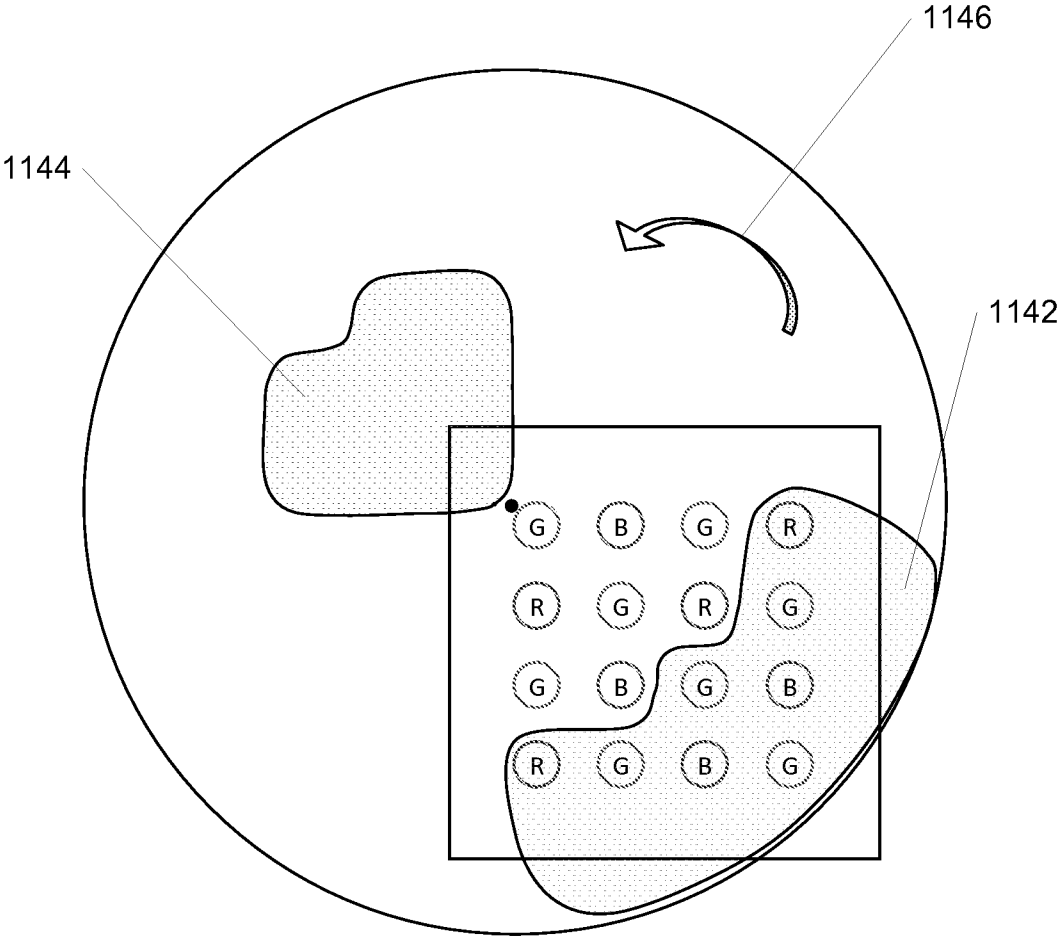


FIG. 11E

1140

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2014/022123

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04N 5/235 (2014.01)

USPC - 348/218.1

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)

IPC(8) - H04N 5/00, 225, 235 (2014.01)

USPC - 348/207.1, 207.11, 218.1; 382/274

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

CPC - H04N 5/00, 225, 235, 2351, 2352, 2355, 2356 (2014.02)

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

PatBase, Google Patents, Google

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/0080487 A1 (VENKATARAMAN et al) 07 April 2011 (07.04.2011) entire document	1
A	US 2009/0274387 A1 (JIN) 05 November 2009 (05.11.2009) entire document	1
A	US 2012/0287291 A1 (MCMAHON) 15 November 2012 (15.11.2012) entire document	1
A	US 2011/0300929 A1 (TARDIF et al) 08 December 2011 (08.12.2011) entire document	1

☐ Further documents are listed in the continuation of Box C.


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"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

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"&amp;" document member of the same patent family

Date of the actual completion of the international search

09 June 2014

Date of mailing of the international search report

25 JUN 2014

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