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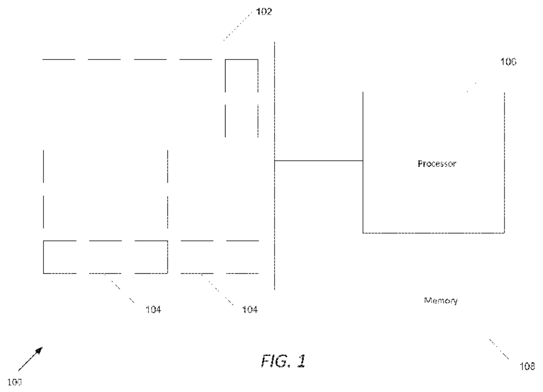

FIG. 1

(57) Abstract: Systems and methods in accordance with embodiments of the invention utilize array cameras incorporating quantum dot color filters. One embodiment includes: lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers form a plurality of optical channels; at least one aperture located within each optical channel; at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of light; and at least one quantum dot color filter located within each optical channel to receive the specific spectral band of light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of light having a bandwidth that is narrower than the specific spectral band of light passed by the at least one spectral filter.

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ARRAY CAMERA IMPLEMENTING QUANTUM DOT COLOR FILTERS

FIELD OF THE INVENTION

[0001] The present invention generally relates to array cameras and more specifically to systems and methods for implementing quantum dot color filters in array cameras.

BACKGROUND

[0002] In capturing an image in a typical camera, light enters through an opening (aperture) at one end of the camera and is directed to a focal plane by an optical array. In most cameras a lens stack including one or more layers of optical elements are placed between the aperture and the focal plane to focus light onto the focal plane. The focal plane consists of light sensitive pixels that generate signals upon receiving light via the optic array. Commonly used light sensitive sensors for use as light sensitive pixels include CCD (charge-coupled device) and CMOS (complementary metal-oxide-semiconductor) sensors.

[0003] Filters are often employed in the camera to selectively transmit lights of certain wavelengths onto the light sensitive pixels. In conventional cameras a Bayer filter mosaic is often formed on the light sensitive pixels. The Bayer filter is a color filter array that arranges one of the RGB color filters on each of the color pixels. The Bayer filter pattern includes 50% green filters, 25% red filters and 25% blue filters. Since each pixel generates a signal representing strength of a color component in the light and not the full range of colors, demosaicing is performed to interpolate a set of red, green and blue values for each pixel.

[0004] Cameras are subject to various performance constraints. The performance constraints for cameras include, among others, dynamic range, signal to noise (SNR) ratio and low light sensitivity. The dynamic range is defined as the ratio of the maximum possible signal that can be captured by a pixel to the total noise signal. The maximum possible signal in turn is dependent on the strength of the incident illumination and the duration of exposure (e.g., integration time, and shutter width). The signal to noise ratio (SNR) of a captured image is, to a great extent, a measure of image quality. In general, as more light is captured by the pixel, the higher the SNR. Accordingly, the SNR of a captured image is usually related to the light gathering capability of the pixel.

[0005] Generally, Bayer filter sensors have low light sensitivity. At low light levels, each pixel's light gathering capability is constrained by the low signal levels incident upon each pixel. In addition, the color filters over the pixel and the necessity to confine the chief ray angle incident on the pixel to avoid cross-talk further constrain the signal reaching the pixel. IR (Infrared) filters also reduce the photo-response from near-IR signals, which can carry valuable information. These performance constraints are greatly magnified in cameras designed for mobile systems due to the nature of design constraints. Pixels for mobile cameras are typically much smaller than the pixels of digital still cameras (DSC) or DSLR's. Due to limits in light gathering ability, reduced SNR, limits in the dynamic range, and reduced sensitivity to low light scenes, the cameras in mobile cameras show poor performance.

[0006] Quantum dots are semiconductor particles that can take any number of shapes including cubes, spheres, pyramids, etc., and have a size that is comparable to the Bohr radius of the separation of electron and hole (exciton). The electronic characteristics of quantum dots are closely related to the size and shape of the individual crystal. In particular, when the size of the quantum dot is smaller than the exciton Bohr radius, the electrons crowd together leading to the splitting of the original energy levels into smaller ones with smaller gaps between each successive level. Thus, if the size of the quantum dot is small enough that the quantum confinement effects dominate (typically less than 10 nm), the electronic and optical properties change, and the fluorescent wavelength is determined by the particle size. In general, the smaller the size of the quantum dot particle, the larger the band gap, the greater becomes the difference in energy between the highest valence band and the lowest conduction band, therefore more energy is needed to excite the dot, and concurrently, more energy is released when the crystal returns to its resting state. For example, in fluorescent dye applications, this equates to higher frequencies of light emitted after excitation of the dot as the crystal size grows smaller, resulting in a color shift from red to blue in the light emitted. Beneficial to this tuning is that a high level of control over the size of the quantum dot particles produced is possible. As a result, it is possible to have very precise control over the fluorescent properties of quantum dot materials.

[0007] Because of their tunability, quantum dots can be assembled into light sensitive quantum films for highly wavelength specific sensors.

SUMMARY OF THE INVENTION

[0008] Systems and methods in accordance with embodiments of the invention utilize array cameras incorporating quantum dot color filters. A lens stack array in accordance with an embodiment of the invention includes: lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels; at least one aperture located within each optical channel; at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of light; and at least one quantum dot color filter located within each optical channel to receive the specific spectral band of light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of light having a bandwidth that is narrower than the specific spectral band of light passed by the at least one spectral filter.

[0009] In another embodiment, the spectral band of light that has a bandwidth that is narrower than the specific spectral band of light is a spectral band that is not contained within the specific spectral band of light.

[0010] An array camera module in accordance with another embodiment includes an imager array including: a plurality of focal planes, where each focal plane comprises a plurality of rows of pixels that also form a plurality of columns of pixels and each focal plane is contained within a region of the imager array that does not contain pixels from another focal plane; control circuitry configured to control the capture of image information by the pixels within the focal planes; and sampling circuitry configured to convert pixel outputs into digital pixel data. The array camera module also includes an optic array of lens stacks aligned with respect to the imager array so that an image is formed on each focal plane by a separate lens stack in said optic array of lens stacks, where the optic array includes: lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels; at least one aperture located within each optical channel; at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of light; and at least one quantum dot color filter located within each optical channel to receive the specific spectral band of light passed by the at least on spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of light having a bandwidth that is narrower than the specific spectral band of light passed by the at least one spectral filter.

[0011] In a still further embodiment, the spectral band of light having a bandwidth that is narrower than the specific spectral band of light is a spectral band that is not contained within the specific spectral band of light.

[0012] A lens stack array in accordance with still another embodiment includes lens elements formed on substrates separated by spacers, where: the lens elements, substrates and spacers form a plurality of lens stacks; each lens stack forms an optical channel; and the lens stack in each optical channel is the same. In addition, at least one aperture located within each optical channel; at least one spectral filter located within each optical channel, where: at least a first optical channel includes at least one spectral filter configured to pass a first spectral band of light; and at least a second optical channel includes at least one spectral filter configured to pass a second spectral band of light; and at least one quantum dot color filter located within each optical channel to receive a specific spectral band of light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter in each optical channel is configured to emit a spectral band of light that is within the same spectral band in response to incident light passed by the at least one spectral filter.

[0013] An array camera module in accordance with a yet further embodiment includes an imager array including: a plurality of focal planes, where each focal plane comprises a plurality of rows of pixels that also form a plurality of columns of pixels and each focal plane is contained within a region of the imager array that does not contain pixels from another focal plane; control circuitry configured to control the capture of image information by the pixels within the focal planes; and sampling circuitry configured to convert pixel outputs into digital pixel data. In addition, the array camera module also includes an optic array of lens stacks aligned with respect to the imager array so that an image is formed on each focal plane by a separate lens stack in said optic array of lens stacks, where the optic array includes: lens elements formed on substrates separated by spacers, where: the lens elements, substrates and spacers form a plurality of lens stacks; each lens stack forms an optical channel; and the lens stack in each optical channel is the same; at least one aperture located within each optical channel; at least one spectral filter located within each optical channel, where: at least a first optical channel includes at least one spectral filter configured to pass a first spectral band of light; and at least a second optical channel includes at least one spectral filter configured to pass a second spectral band of light; and at least one quantum dot color filter located within each optical channel to receive the specific spectral band of light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter in each optical channel is configured to emit a spectral band of light that is within the same spectral band in response to incident light passed by the at least one spectral filter.

[0014] A lens stack array in accordance with a further embodiment again includes lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels; at least one aperture located within each optical channel; at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of ultraviolet light; and at least one quantum dot color filter located within each optical channel to receive the specific spectral band of ultraviolet light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of visible light in response to incident ultraviolet light passed by the at least one spectral filter.

[0015] An array camera module in accordance with another embodiment again includes an imager array including: a plurality of focal planes, where each focal plane comprises a plurality of rows of pixels that also form a plurality of columns of pixels and each focal plane is contained within a region of the imager array that does not contain pixels from another focal plane; control circuitry configured to control the capture of image information by the pixels within the focal planes; and sampling circuitry configured to convert pixel outputs into digital pixel data. In addition, the array camera module also includes an optic array of lens stacks aligned with respect to the imager array so that an image is formed on each focal plane by a separate lens stack in said optic array of lens stacks, where the optic array including: lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels; at least one aperture located within each optical channel; at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of ultraviolet light; and at least one quantum dot color filter located within each optical channel to receive the specific spectral band of ultraviolet light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of visible light in response to incident ultraviolet light passed by the at least one spectral filter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a block diagram of an array camera in accordance with an embodiment of the invention.

[0017] FIG. 2 conceptually illustrates an optic array and an imager array in an array camera module in accordance with an embodiment of the invention.

[0018] FIG. 3A is a block diagram of an imager array in accordance with an embodiment of the invention.

[0019] FIG. 3B is a cross-sectional illustration of a camera channel incorporating a light sensitive quantum film sensor in accordance with an embodiment of the invention.

[0020] FIG. 4 is a plan view of a camera array having spectral filtration applied at the camera level in accordance with an embodiment of the invention.

[0021] FIG. 5A conceptually illustrates a Bayer filter applied at the pixel level of a light sensitive element.

[0022] FIG. 5B conceptually illustrates a graph of an idealized spectral transmission of a color filter versus the wavelength of light.

[0023] FIG. 6 conceptually illustrates a Bayer filter lens stack in operation filtering white light.

[0024] FIG. 7 conceptually illustrates a conventional array camera filter lens stack in operation filtering white light.

[0025] FIG. 8 conceptually illustrates an array camera implementing quantum dot filters in operation filtering white light in accordance with an embodiment of the invention.

[0026] FIG. 9A is a cross-sectional illustration of a camera channel incorporating vertical optical isolation arrangements in accordance with an embodiment of the invention.

[0027] FIG. 9B is a cross-sectional illustration of a camera channel incorporating horizontal optical isolation arrangements in accordance with an embodiment of the invention.

[0028] FIG. 10 is a block diagram of an imager array in accordance with an embodiment of the invention.

[0029] FIG. 11 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.

DETAILED DISCLOSURE OF THE INVENTION

[0030] Turning now to the drawings, systems and methods for implementing quantum dot color filters on array cameras in accordance with embodiments of the invention are illustrated. Many embodiments relate to using quantum dot films color filters in camera modules of array cameras.

[0031] Array cameras including camera modules that can be utilized to capture image data from different viewpoints (i.e. light field images) are disclosed in U.S. Patent Application Serial No. 12/935,504 entitled “Capturing and Processing of Images using Monolithic Camera Array with Heterogeneous Imagers” to Venkataraman et al. In many instances, fusion and super-resolution processes such as those described in U.S. Patent Application Serial No. 12/967,807 entitled “Systems and Methods for Synthesizing High Resolution Images Using Super-Resolution Processes” to Lelescu et al., can be utilized to synthesize a higher resolution 2D image or a stereo pair of higher resolution 2D images from the lower resolution images in the light field captured by an array camera. The terms high or higher resolution and low or lower resolution are used here in a relative sense and not to indicate the specific resolutions of the images captured by the array camera. The disclosures of U.S. Patent Application 12/935,504 and U.S. Patent Application Serial No. 12/967,807 are hereby incorporated by reference in their entirety.

[0032] Each two-dimensional (2D) image in a captured light field is from the viewpoint of one of the cameras in the array camera. Due to the different viewpoint of each of the cameras, parallax results in variations in the position of foreground objects within the images of the scene. Processes such as those disclosed in U.S. Provisional Patent Application No. 61/691,666 entitled “Systems and Methods for Parallax Detection and Correction in Imaged Captured Using Array Cameras” to Venkataraman et al. can be utilized to provide an accurate account of the pixel disparity as a result of parallax between the different cameras in an array. The disclosure of U.S. Patent Application Serial No. 61/691,666 is hereby incorporated by reference in its entirety. Array cameras can use disparity between pixels in images within a light field to generate a depth map from a reference viewpoint. A depth map indicates the distance of the surfaces of scene objects from the reference viewpoint and can be utilized to determine scene dependent geometric corrections to apply to the pixels from each of the images within a captured light field to eliminate disparity when performing fusion and /or super-resolution processing.

[0033] In further embodiments, each camera in an array camera may include separate optics with different filters and operate with different operating parameters (e.g., exposure time). In many embodiments, the separate optics incorporated into each imager are implemented using a lens stack array. The lens stack array can include one or more optical elements, including color filters, that can be fabricated using wafer level optics (WLO) technology and/or any other technology appropriate for manufacturing lens stack arrays. In many embodiments, each of the camera channels may be configured with special quantum dot color filters such that color separation is performed at a camera channel level with a minimum possible color aberration. Systems and methods for using quantum dot color filters in array cameras in accordance with embodiments of the invention are discussed further below.

Array Cameras

[0034] 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. Multiple camera arrays may operate in conjunction to provide extended functionality over a single camera array, such as, for example, stereo resolution.

Array Camera Modules

[0035] 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 242 within a corresponding focal plane 240. As is described further below, the light sensitive pixels 242 can be formed from quantum films. 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. The camera module may be fabricated on a single chip for mounting or installing in various devices.

[0036] 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.

Imager Arrays

[0037] Imager arrays in accordance with embodiments of the invention can be constructed from an array of focal planes formed of arrays of light sensitive pixels. As discussed above in relation to FIG. 2, in many embodiments the imager array 230 is composed of multiple focal planes 240, each of which have a corresponding lens stack 220 that directs light from the scene through the optical channel and onto a plurality of light sensing elements formed on the focal plane 240. In many embodiments the light sensing elements are formed on a CMOS device using photodiodes formed in the silicon where the depleted areas used for photon to electron conversion are disposed at specific depths within the bulk of the silicon. In some embodiments, a focal plane of an array of light sensitive pixels formed from a quantum film sensor may be implemented. The formation, composition, performance and function of various quantum films, and their use in optical detection in association with semiconductor integrated circuits are described in U.S. Patent Publication US/2009/0152664, entitled “Materials, Systems and Methods for Optoelectronic Devices”, published June 18, 2009, the disclosure of which is incorporated by reference herein in its entirety.

[0038] A focal plane in accordance with an embodiment of the invention is illustrated in FIGS. 3A and 3B. The focal plane 300 includes a focal plane array core 310 that includes an array of light sensitive pixels 330 disposed at the focal plane of the lens stack 350 of a camera 360 on a semiconducting integrated circuit substrate 340, such as a CMOS or CCD. The focal plane can also include all analog signal processing, pixel level control logic, signaling, and analog-to-digital conversion (ADC) circuitry used in the readout of pixels. The lens stack 350 of the camera 360 directs light from the scene and onto the light sensitive pixels 330. The formation, architecture and operation of imager arrays and light sensitive pixel arrays, and their use in optical detection in association with array cameras are described in U.S. Patent App. 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.

Camera Level Color Filter Implementation

[0039] In order to obtain information about the color of an image, light can be separated into spectral bands and then directed to different color channels. As illustrated in FIG. 4, in many embodiments of the array camera (400), color filters (410) differentiated at the camera level (420) can be used to pattern the camera module. Example filters include a traditional filter used in the Bayer pattern (R, G, B or their complements C, M, Y), an IR-cut filter, a near-IR filter, a polarizing filter, and a custom filter to suit the needs of hyper-spectral imaging. The number of distinct filters may be as large as the number of cameras in the camera array. Embodiments where π filter groups are formed is 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. Instead of applying color filters at the pixel level of the camera, color filters in many embodiments of the invention are included in the lens stack of the camera. 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.

[0040] The ability to apply color filter at a camera level and not at a pixel level means that the color filter may be applied either directly at the focal plane or in the lens stack. Accordingly, in some embodiments the color filter is applied at the focal plane directly on the light sensitive elements across the entire camera and not at the pixel level. Alternatively, in other embodiments the color filter is applied within the lens stack of the camera and not at the focal plane. Placing the color filter within the lens stack means any light reaching the pixel array on the focal plane is an integration of all the light that goes through every part of the color filter on the lens stack. This has the advantage of averaging the effective intensity of the color filtered light on the pixel array with the result that the homogeneity of the filtered light is excellent over the entire pixel array. This homogeneity can be compromised when the color filter is applied on the pixel array directly, because variations in the thickness of the color filter from one pixel to another may affect the intensity of the filtered light at that pixel leading to a pixel response non-uniformity.

[0041] Although a specific construction of camera modules with an optic array including color filters in the lens stacks is described above, camera modules including color filters and π filter groups can be implemented in a variety of ways. 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 either as the sole color filter or in combination with a camera level filter. In some 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.

Quantum Dot Color Filters

[0042] As described, the separation of spectral channels in camera arrays at the camera level achieves elimination of inter color crosstalk in the active pixel array – a major source of noise in pixels with the conventional Bayer color filters, which are typically applied at the pixel level (500), as illustrated in FIG. 5A. Implementation of color filters in the optical channels of camera arrays also allows for a relaxation in the optic requirements. However, another aspect that is important to optimizing the efficiency of the optical channels is the full-width half-max spectral bandwidth of the color filters themselves. FIG. 5B shows a conceptual graph of an idealized spectral transmission of a color filter versus the wavelength of light. The attributes ‘a’ and ‘b’ together define the full-width half-max bandwidth of the filter curve, or in other words the amount of information carrying capacity of the filter band. This attribute exemplifies the bandwidth of the spectral filter and identifies the space over which the optical channel needs to have good MTF performance. However, the width of this spectral bandwidth has many aspects to consider in designing a good filter for faithful color capture. First, the width ‘a’ and height ‘b’ of the spectral bandwith determine the sensitivity of the channel to light and the larger this width (up to the limits of typical human vision) the greater the sensitivity of the imaging system. Beyond this critical width, while light sensitivity is gained, the spectral fidelity is lost since the filter band begins to deviate from that of typical human visual system. Second, the width ‘a’ also determines the level of spectral crosstalk between the primary colors (for example: red, green, or blue) that are captured by the imaging system. Accordingly, the design of the filters is a complex process that seeks to optimize the sensitivity and spectral fidelity versus the crosstalk to achieve a balanced color reproduction system. Too large a width results in larger spectral crosstalk and correspondingly poorer spectral fidelity. While, too narrow a width trades away sensitivity of the spectral channel.

[0043] The rigor of an optical design for camera arrays can be defined by the spectral range over which the optics has to achieve optimal MTF. In general, the larger the spectral width the more difficult the design becomes and the larger the number of lens elements that are required to address the aberrations that result. This is because the size of the wavefront aberrations scale with the lens size to the power of up to 4. So, there is a desire to keep this spectral width as small as possible (subject to sensitivity) to simplify the design constraints for array optics and to give the designer more degrees of freedom to achieve the design objectives. As discussed above, imaging systems that use a Bayer color filter on their active pixel array also have to deal with a certain amount of electrical and optical color crosstalk that can compromise the spectral fidelity.

Consequently, the filters designed for such systems are typically wider than optimal to pre-compensate for the sensitivity lost in the crosstalk. For example, FIG. 6 illustrates a conventional optical stack employed in a legacy camera (600). Here, there is no spectral channel separation in the optical stack (610) and the color separation is achieved through Bayer filters (620) in the active pixel arrays on the sensor. Consequently, the optical design employs a polychromatic lens (630) or optical design that is required to optimize the MTF over the entire visible range of wavelengths (λ_{Bayer}) required to capture the full color profile of the imaging system. This results in an overall degradation in the MTF as none of the optics or sensors can be optimized for specific spectral bands.

[0044] As illustrated in FIG. 7 and discussed above, in a camera array it is possible to reduce the spectral range over which any sensor or lens stack must operate by employing a conventional color filter in the optical stack and thereby forming separate spectral channels for each of the primary colors (for example: blue, green, and red). As shown, in these embodiments the spectral color filters (710) filter the incoming white light (720) into the separate spectral colors (730) required for each of the optical channels (740) in the camera array. Thus, incoming white light is filtered into components, such as, for example, blue, green, and red light that is then captured by the individual optics for the separate spectral channel. In this configuration, each of the optics only has to have their MTF optimal over the spectral range defined by the respective color filters resulting in a much reduce spectral range (λ_{ca}) for these camera arrays as compared to the Bayer filter legacy camera to which polychromatic optics must be designed.

[0045] Quantum dot filters utilized in accordance with embodiments of the invention may employ colloidal quantum dots that are quantum size-effect tunable. This tunability means that quantum films may be made that are either homogeneous (meaning that they incorporate a mixture of quantum dots with different spectral absorption/emission characteristics) such that the film is sensitive to light across a wide spectral range (from UV-VIS to IR) and emits a broadband light, or structured such that only quantum dots that absorb over a specific spectral band or that emit a very narrow wavelength of light are included in the film. It should be understood that spectral bands for which structured films can be formed are not limited to any spectral region and may include X-ray, UV, visible (including specific spectral bands within the visible spectrum such as red, green, and blue), near-infrared, and short-wavelength infrared. The formation and color matching of quantum dots, and their use in optical devices are described in U.S. Patent No. 8,227,979, entitled “Method of Matching Color in Lighting Applications”, issued July 24, 2012, the disclosure of which is incorporated by reference herein in its entirety.

[0046] FIG. 8 illustrates embodiments of a quantum dot color filter enhanced optical stack for the camera array. In this embodiment each camera (800) would include two sets of filters, first a conventional spectral color filter (810) to filter the incoming white light (820) into separate spectral bands (830) (such as for example, blue, green and red spectral bands). The spectral bands (830) of each channel (840) are then sent through a quantum dot color filter (850), each of these quantum dot color filters being selected to emit an optimized spectral range (λ_{min}). Because the quantum dots are intimately tunable based on size, as described above, these quantum color filters have the property of emitting at a very well-defined narrow wavelength band, upon absorbing a photon. Although the emission from the quantum color filter may take any narrow band shape, in some embodiments it may be defined by a very tight Gaussian distribution. As the emission wavelength of the quantum dots is independent of the wavelength of the incoming excitation photon, the quantum dot color filter is capable of shifting each incoming photon to any selected and specific output wavelength (such as, for example, to a narrow part of the red spectral band, as shown in FIG. 8). Each of these narrow spectral bands could then be mapped to the desired color in the signal processing stage. Since, the amount of charge captured by the sensor is a function of the quantum efficiency of the sensor, there is no loss of sensitivity in this process (as long as the QE of the sensor in the narrow part of the red spectral band is not any less than the corresponding value in the traditional camera array).

[0047] Although embodiments in which the incoming photons are shifted within the visible spectrum are described, it other embodiments it would be possible to translate incoming photon into and out of the visible spectrum. For example, in some embodiments a photon in the ultraviolet spectrum could be translated into the visible region, thereby allowing CMOS sensors to image in these non-visible spectra. This could be useful, for example, in allowing cameras to capture subjects in near darkness and/or within portions of the frequency spectral that are not typically able to be imaged using conventional CMOS sensors.

[0048] Accordingly, embodiments of a quantum dot color filter can achieve a minimal spectral range over which the MTF is optimized for each optic channel. This spectral range is much reduced from that of the traditional camera array, and can be as small as desired without compromising any of the other attributes such as sensitivity or spectral fidelity. The reduction in the spectral range for the optics has other important advantages in the optical design process, as will be described in greater detail below.

Optics Design

[0049] Another advantage of the quantum dot filters relates to the design of the optics and addressing chromatic aberrations. Specifically, as discussed in brief above, in a conventional polychromatic lens, and to a lesser extent in conventional camera arrays, the lens/lenses have to be corrected for chromatic aberrations, because the focal length through the lens is different for different wavelengths of light. As a result, it is necessary to compromise the performance of the lens for some of the color wavelengths to get acceptable overall color performance. By making each optical channel narrow spectral band through the quantum dot filter, color aberration is reduced and/or prevented, and each lens may be optimized to the specific color wavelength. For example, an imager receiving visible or near-IR spectrum may have a lens element specifically optimized for this spectral band of light. For imagers detecting other light spectrum, the lens element may be constructed with different properties, such as radii of curvature, so that a constant focal length across all wavelengths of light is achieved so that, in turn, the focal plane is the same for different spectral bands of light. The matching of the focal plane across different wavelengths of light increases the sharpness of image captured at the imager and reduces longitudinal chromatic aberration. Because each lens element may be designed to direct a narrow band of light, the concomitant lack of color aberration means that the lens elements can be subject to less rigorous design constraints, yet produce better or equivalent performance compared to a conventional lens element covering a wide light spectrum. In particular, there is no need to undertake costly aberration balancing correction. What is more, simple lenses generally have better MTF and lower F# (higher sensitivity). It should be noted that although the lenses used in these array cameras have much smaller color aberrations when compared to conventional lenses, each lens is still designed to focus a certain albeit extremely narrow wavelength-bandwidth. Accordingly, in one embodiment each of these “monochromatic” lenses can be optimally color corrected by using combinations of high and low Abbe number materials (different optical dispersions).

[0050] Light of different wavelengths having different focal lengths (longitudinal color aberration) is not the only type of aberration that occurs in polychromatic optical systems. The refractive index of a lens is dependent on the wavelength of light passing through the lens. As a result, a lens will impart different magnification to colors of different wavelengths. For example, the red wavelength band might have a slightly smaller magnification than green, and green may in turn have a slightly smaller magnification than blue. If the images obtained from these different wavelengths of light are then overlaid without correction, the image will lose resolution because the different colors will not overlap correctly. Based on the properties of the material, the differential lateral distortions of the color magnification can be determined and then corrected. Correction can be accomplished by restricting the profiles of the lenses so that each color has the same magnification, but this reduces the possible degrees of freedom available for lens manufacture, and reduces the ability to optimize MTF. Accordingly, lateral distortion can be permitted optically, and then corrected after imaging computationally. The electronic correction of the lateral color of the lens can actually provide improvements to system performance above and beyond simply correcting for the original distortion, because such correction directly improves the resolution of the system in terms of polychromatic MTF. In particular, lateral color aberrations in a lens can be seen as a color dependent distortion of the lens. By mapping all differently distorted single color images of an object back to the same rectangle, perfect overlap can be achieved in the full color image resulting in the polychromatic MTF being the same as the monochromatic one (not only due to the individual color channel color-blur correction, but also as a result of the exact superposition of the different colors). However, using the quantum dot color filters allows for the minimization of these lateral color aberrations also.

[0051] Yet another advantage to using lenses optimized for use with a narrow band of light, is that the there is no restriction on the type of lens that may be used. In particular, the array camera allows for the use of diffractive, refractive, Fresnel lenses, or combinations of these types of lenses. Diffractive lenses are attractive because they allow for the creation of complex wavefronts with an essentially flat optical element, and they are also relatively simple to manufacture. In conventional cameras it is not possible to use diffractive lenses because having a single imager means that the lens must be able to efficiently transmit a wide spectrum of light, and while diffractive lenses are very efficient at transmitting narrow wavelength bands of light, there is a steep drop-off in performance for wavelengths of light outside of this optimized range. Because each array of the current camera may be focused on a narrow wavelength of light, the narrow optimized wavelength band of these diffractive lenses is not a limiting factor.

[0052] Accordingly, in many embodiments, color filters for camera array systems that minimize the width of the spectral channel to the minimum necessary to achieve sufficient spectral crosstalk for good spectral fidelity by implementing quantum dot and quantum film materials are used.

Lens Stack Arrangements

[0053] In many embodiments, filters are part of the imager. In other embodiments, filters are part of a lens stack. In an embodiment including a filter, it is preferred to dispose the filter (whether CFA, IR and/or VIS) in the lens stack at or close to the aperture stop surface and not at the imager sensor surface, because when positioned at a distance from the imager sensor small defects in those filter layers are averaged out over all entrance pupil positions, and are therefore less visible. Some other potentially beneficial elements that can be incorporated in the lens stacks in accordance with embodiments are described below.

[0054] In some embodiments the lens stack may also include optical crosstalk suppressors for ensuring that light impinging on any particular focal plane comes only from its designated optical pathway or channel. Optical crosstalk suppressors used in accordance with embodiments of the invention are shown in FIGs 9A and 9B. Optical crosstalk can be considered to occur when light that is supposed to be incident on the top of one focal plane is instead also received by light sensing elements of another focal plane within the array. Accordingly, in many embodiments optical channels of the camera array are optically isolated so that a ray of light from one optical channel cannot cross to another optical channel. In some embodiments, illustrated in FIG. 9A, lens stacks 900 are formed with opaque spacers 910 or vertical opaque walls 920, which may be disposed between the optical channels 930. Although opaque spacers do provide a level of optical crosstalk suppression, vertical opaque walls are preferable because in such an embodiment both the space between substrates and the relevant sections of the substrates themselves are rendered non-transparent. In other embodiments, shown schematically in FIG. 9B, optical crosstalk suppression is achieved by creating a virtual opaque wall formed by a series of stacked apertures. In this embodiment, a series of aperture stops are formed on the various substrate levels 940 of the optical channel 900 by coating the substrates with opaque layers 950 provided with a narrow opening or aperture 960. If enough of these apertures are formed, it is possible to mimic the optical isolation provided by a vertical opaque wall. In such a system, a vertical wall would be the mathematical limit of stacking apertures one on top of each other. Preferably, as many apertures as possible, separated from each other by sufficient space, are provided so that such a virtual opaque wall is created. For any lens stack, the number and placement of opaque layers needed to form such a virtual vertical opaque wall can be determined through a ray tracing analysis. Although specific structures and components for preventing optical crosstalk are described, any of a variety of arrangement for reducing crosstalk can be constructed in accordance with embodiments of the invention.

[0055] Although embodiments of optical arrangements for use in an array camera that captures images using a distributed approach using a quantum dot filter are described above, it should be understood that other optical elements and arrangements may be fabricated for use with embodiments of the array camera. Embodiments where various lens stacks are incorporated into array cameras is further discussed in U.S. Patent Application No. 13/536,520 entitled “Optical Arrangements for Use With An Array Camera” filed June 28, 2012, the disclosure of which is incorporated by reference herein in its entirety.

Imager Array Control

[0056] 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. 10. The imager array 1000 includes a focal plane array core 1002 that includes an array of focal planes 1004 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 1006 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 1006 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 1008. The power management and bias generation circuitry 1008 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 1010 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.

[0057] In many embodiments, a single self-contained chip imager includes focal plane framing circuitry 1012 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 1016, interface control circuitry 1016 and interface input circuitry 1018. 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.

[0058] Although specific components of an imager array architecture are discussed above with respect to FIG. 10, 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

[0059] 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. The ability to configure active focal planes using difference image capture settings can enable different cameras within an array camera to make independent measurements of scene information that can be combined for use in determining image capture settings for use more generally within the camera array.

[0060] 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. 11. The imager array 1100 includes a plurality of focal planes or pixel sub-arrays 1102. Control circuitry 1103, 1104 provides independent control of the exposure timing and amplification gain applied to the individual pixels within each focal plane. Each focal plane 1102 includes independent row timing circuitry 1106, 1108, and independent column readout circuitry 1110, 1112. In operation, the control circuitry 1103, 1104 determines the image capture settings of the pixels in each of the active focal planes 1102. The row timing circuitry 1106, 1108 and the column readout circuitry 1110, 1112 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 1116.

[0061] Although specific imager array configurations are discussed above with reference to FIG. 11, 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. The use of independent focal plane control to capture image data using array cameras is discussed further below.

[0062] 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 lens stack array, comprising:

lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels;

at least one aperture located within each optical channel;

at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of light; and

at least one quantum dot color filter located within each optical channel to receive the specific spectral band of light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of light having a bandwidth that is narrower than the specific spectral band of light passed by the at least one spectral filter.

2. The lens stack array of claim 1, wherein the spectral band of light that has a bandwidth that is narrower than the specific spectral band of light is a spectral band that is not contained within the specific spectral band of light.

3. An array camera module comprising:

an imager array including:

a plurality of focal planes, where each focal plane comprises a plurality of rows of pixels that also form a plurality of columns of pixels and each focal plane is contained within a region of the imager array that does not contain pixels from another focal plane;

control circuitry configured to control the capture of image information by the pixels within the focal planes; and

sampling circuitry configured to convert pixel outputs into digital pixel data; and an optic array of lens stacks aligned with respect to the imager array so that an image is formed on each focal plane by a separate lens stack in said optic array of lens stacks, where the optic array comprises:

lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels;

at least one aperture located within each optical channel;

at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of light; and

at least one quantum dot color filter located within each optical channel to receive the specific spectral band of light passed by the at least on spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of light having a bandwidth that is narrower than the specific spectral band of light passed by the at least one spectral filter.

4. The array camera module of claim 3, wherein the spectral band of light having a bandwidth that is narrower than the specific spectral band of light is a spectral band that is not contained within the specific spectral band of light.

5. A lens stack array, comprising:

lens elements formed on substrates separated by spacers, where:

the lens elements, substrates and spacers form a plurality of lens stacks;

each lens stack forms an optical channel; and

the lens stack in each optical channel is the same;

at least one aperture located within each optical channel;

at least one spectral filter located within each optical channel, where:

at least a first optical channel includes at least one spectral filter configured to pass a first spectral band of light; and

at least a second optical channel includes at least one spectral filter configured to pass a second spectral band of light; and

at least one quantum dot color filter located within each optical channel to receive a specific spectral band of light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter in each optical channel is configured to emit a spectral band of light that is within the same spectral band in response to incident light passed by the at least one spectral filter.

6. An array camera module comprising:

an imager array including:

a plurality of focal planes, where each focal plane comprises a plurality of rows of pixels that also form a plurality of columns of pixels and each focal plane is contained within a region of the imager array that does not contain pixels from another focal plane;

control circuitry configured to control the capture of image information by the pixels within the focal planes; and

sampling circuitry configured to convert pixel outputs into digital pixel data; and

an optic array of lens stacks aligned with respect to the imager array so that an image is formed on each focal plane by a separate lens stack in said optic array of lens stacks, where the optic array comprises:

lens elements formed on substrates separated by spacers, where:

the lens elements, substrates and spacers form a plurality of lens stacks;

each lens stack forms an optical channel; and

the lens stack in each optical channel is the same;

at least one aperture located within each optical channel;

at least one spectral filter located within each optical channel, where:

at least a first optical channel includes at least one spectral filter configured to pass a first spectral band of light; and

at least a second optical channel includes at least one spectral filter configured to pass a second spectral band of light; and

at least one quantum dot color filter located within each optical channel to receive the specific spectral band of light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter in each optical channel is configured to emit a spectral band of light that is within the same spectral band in response to incident light passed by the at least one spectral filter.

7. A lens stack array, comprising:

lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels;

at least one aperture located within each optical channel;

at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of ultraviolet light; and

at least one quantum dot color filter located within each optical channel to receive the specific spectral band of ultraviolet light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of visible light in response to incident ultraviolet light passed by the at least one spectral filter.

8. An array camera module comprising:

an imager array including:

a plurality of focal planes, where each focal plane comprises a plurality of rows of pixels that also form a plurality of columns of pixels and each focal plane is contained within a region of the imager array that does not contain pixels from another focal plane;

control circuitry configured to control the capture of image information by the pixels within the focal planes; and

sampling circuitry configured to convert pixel outputs into digital pixel data; and

an optic array of lens stacks aligned with respect to the imager array so that an image is formed on each focal plane by a separate lens stack in said optic array of lens stacks, where the optic array comprises:

lens elements formed on substrates separated by spacers, where the lens elements, substrates and spacers are configured to form a plurality of optical channels;

at least one aperture located within each optical channel;

at least one spectral filter located within each optical channel, where each spectral filter is configured to pass a specific spectral band of ultraviolet light; and

at least one quantum dot color filter located within each optical channel to receive the specific spectral band of ultraviolet light passed by the at least one spectral filter located within the optical channel, where the at least one quantum dot color filter is configured to emit a spectral band of visible light in response to incident ultraviolet light passed by the at least one spectral filter.

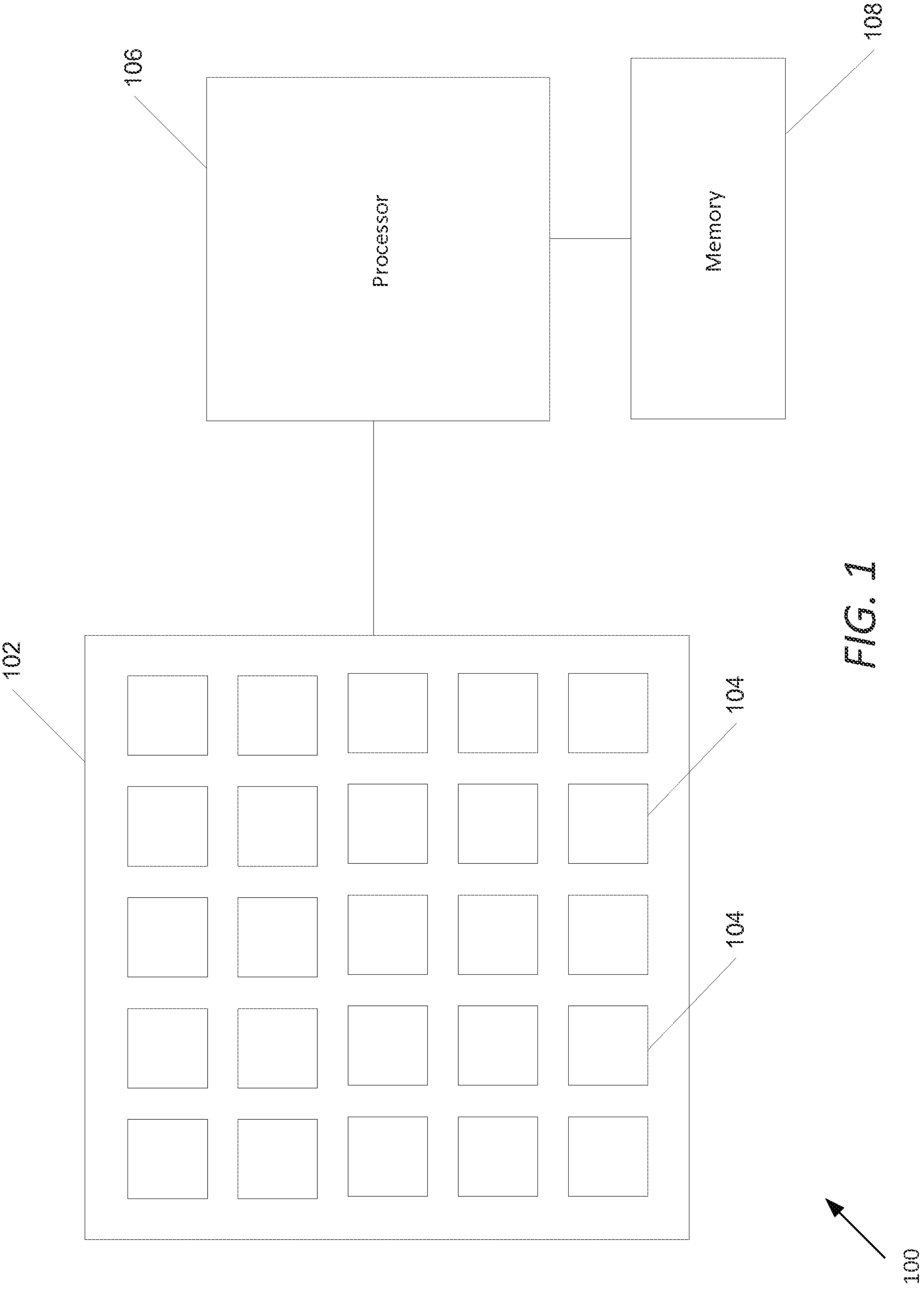

FIG. 1

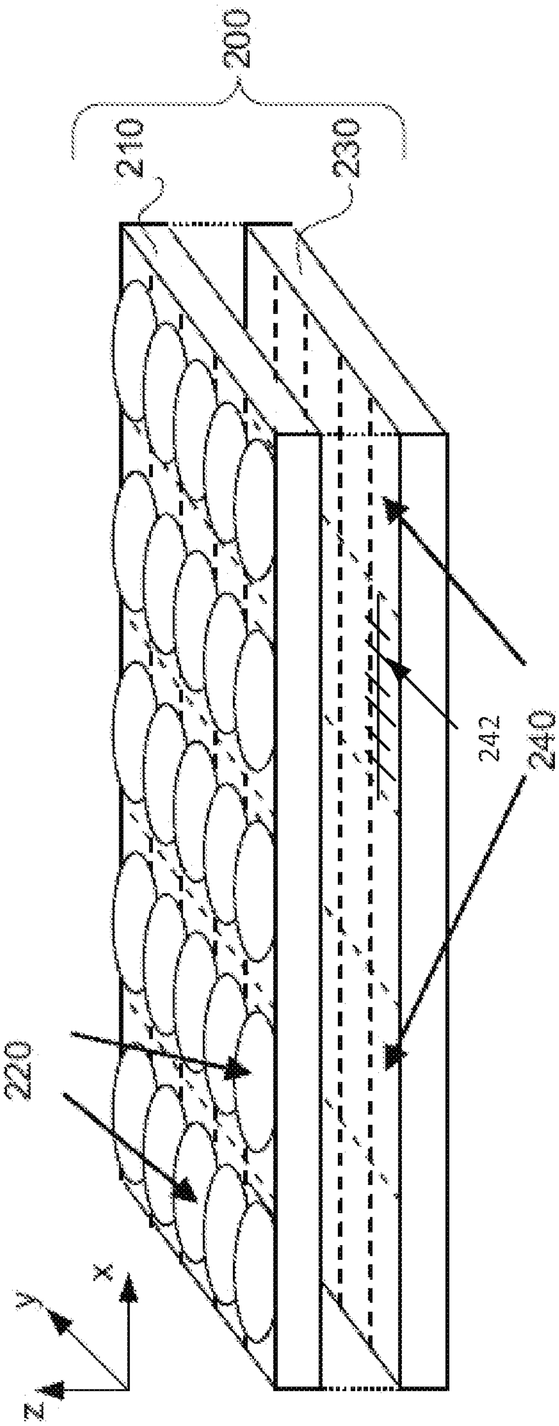

FIG. 2

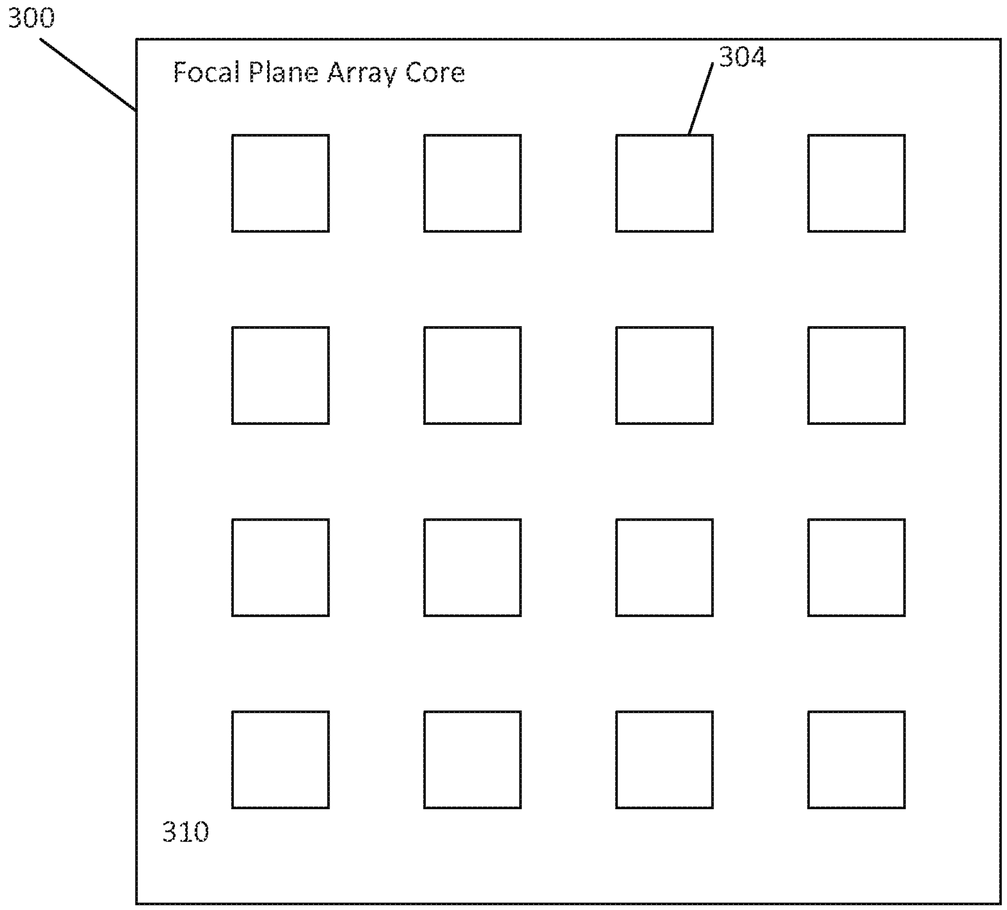

FIG. 3A

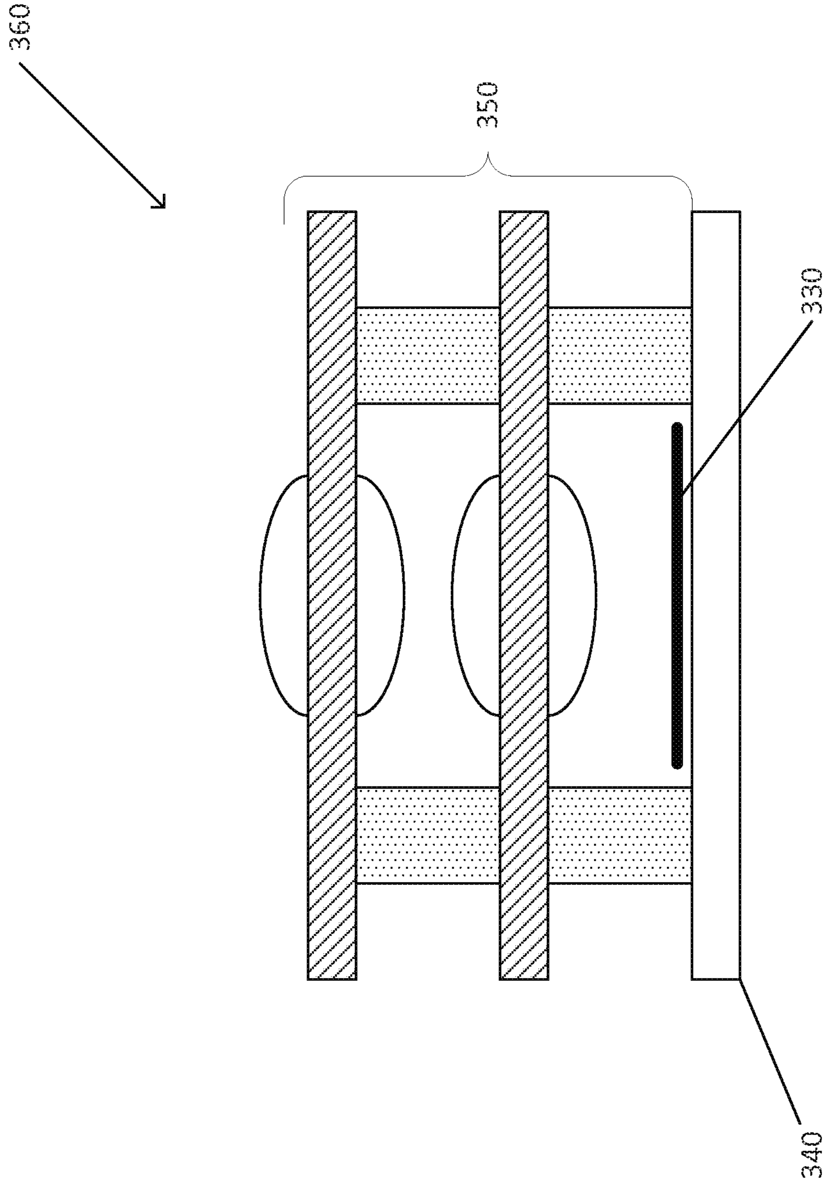

FIG. 3B

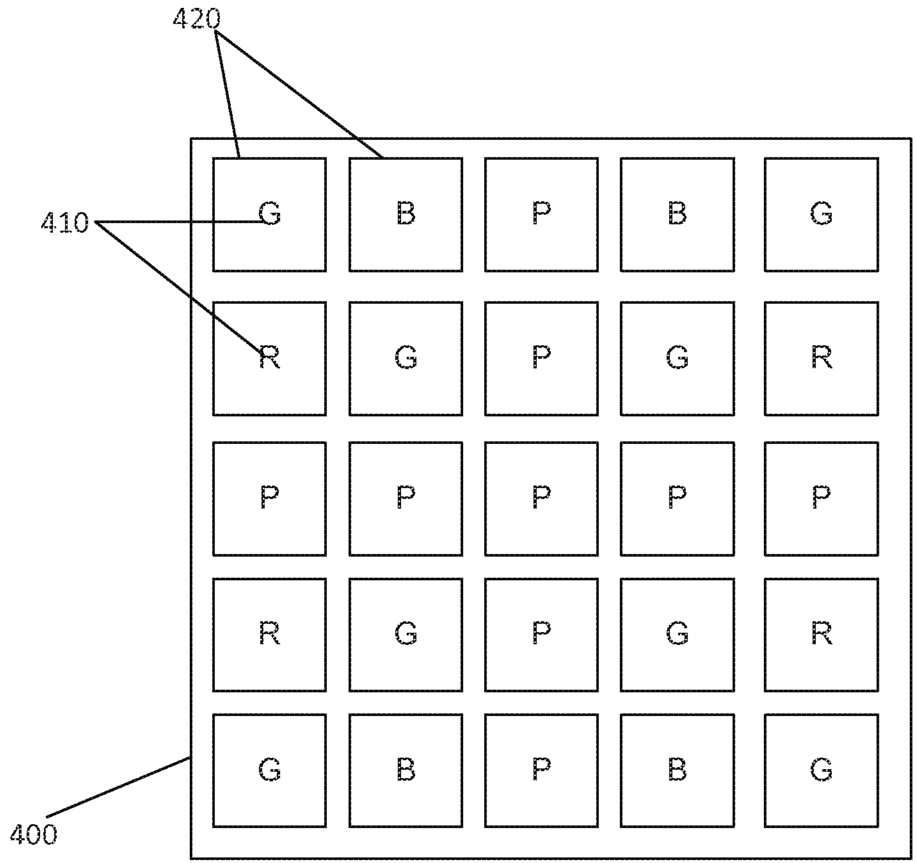

FIG. 4

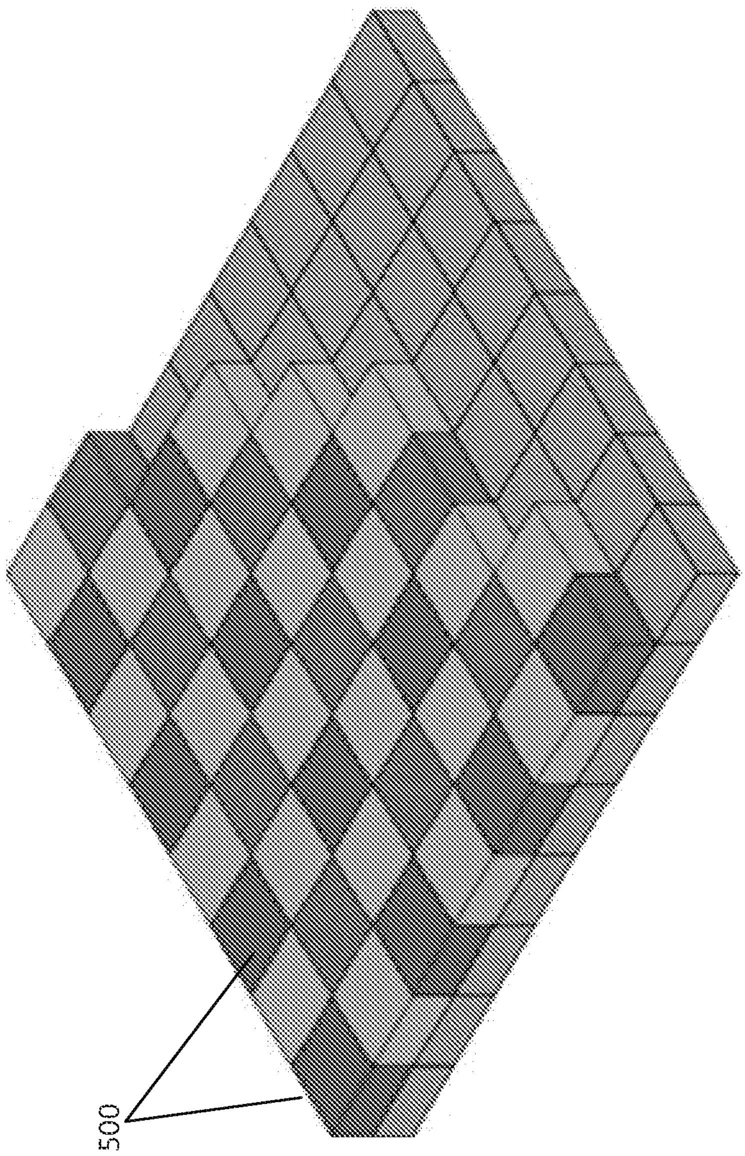

FIG. 5A

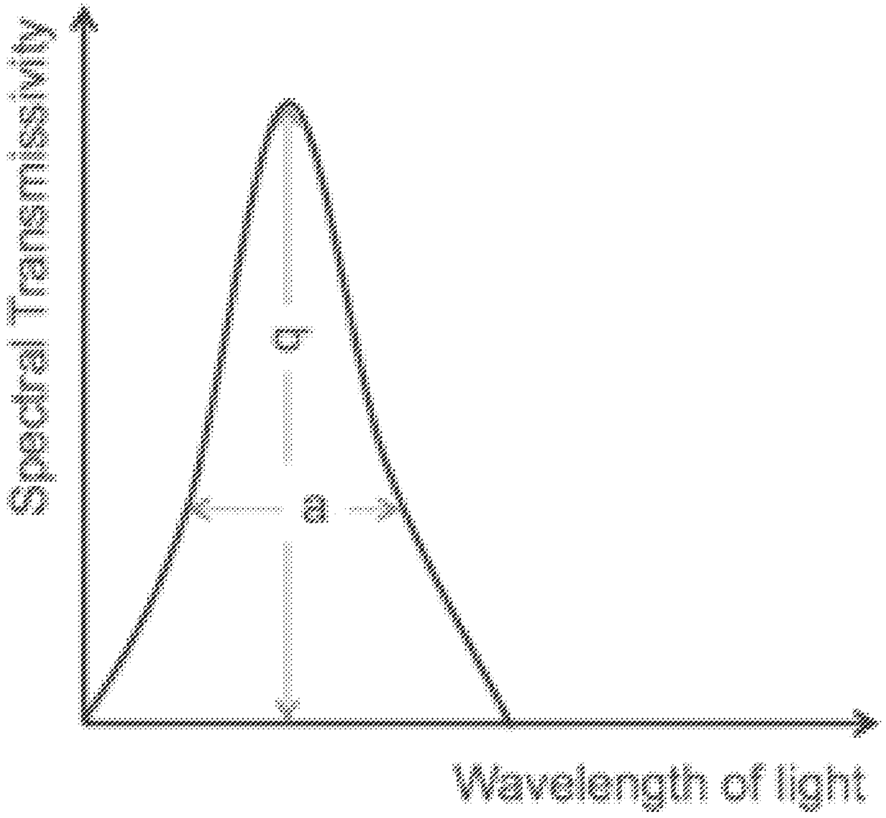

FIG. 5B

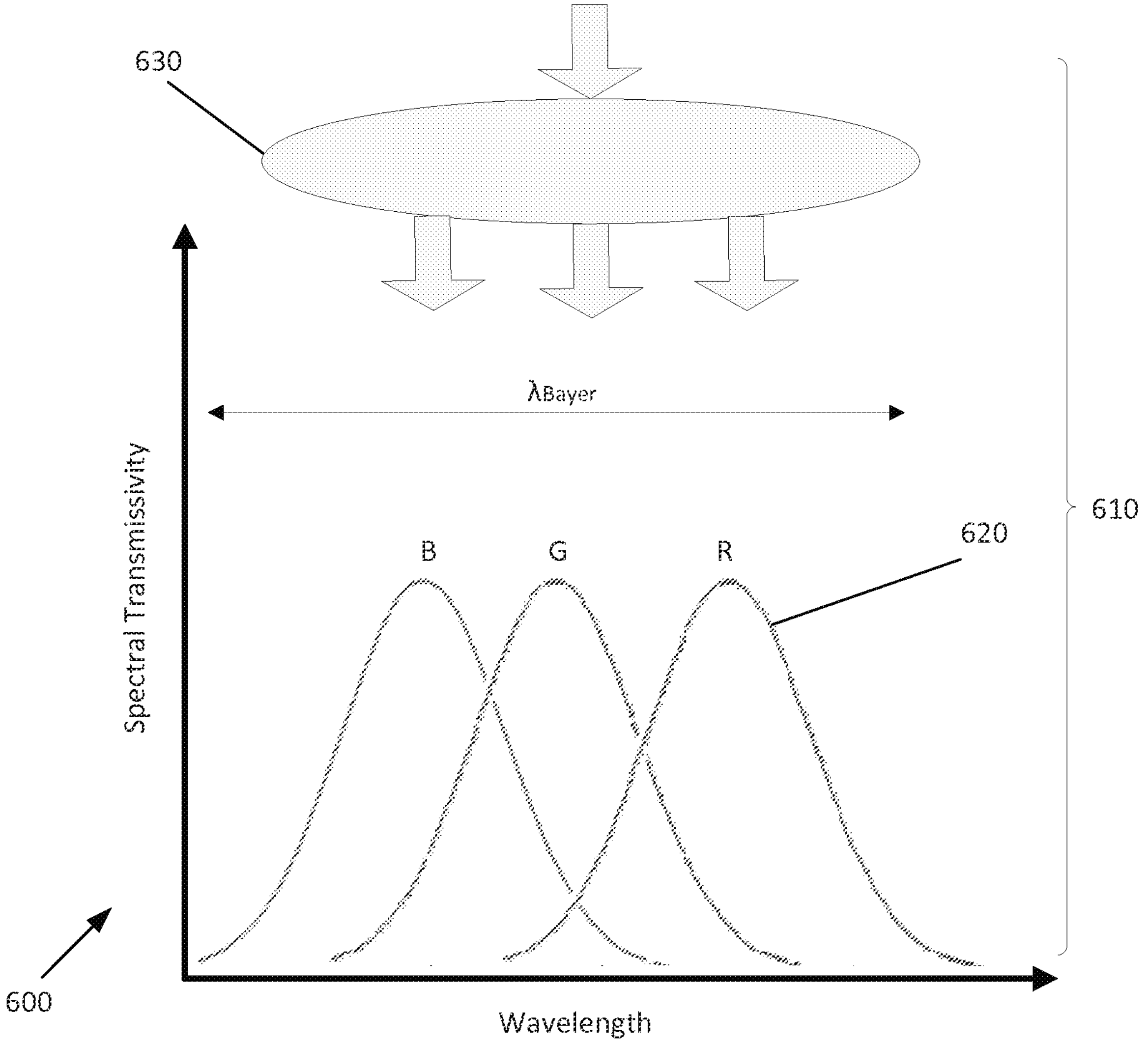
630
λBayer
Spectral Transmissivity
B
G
R
620
610
600
Wavelength

FIG. 6

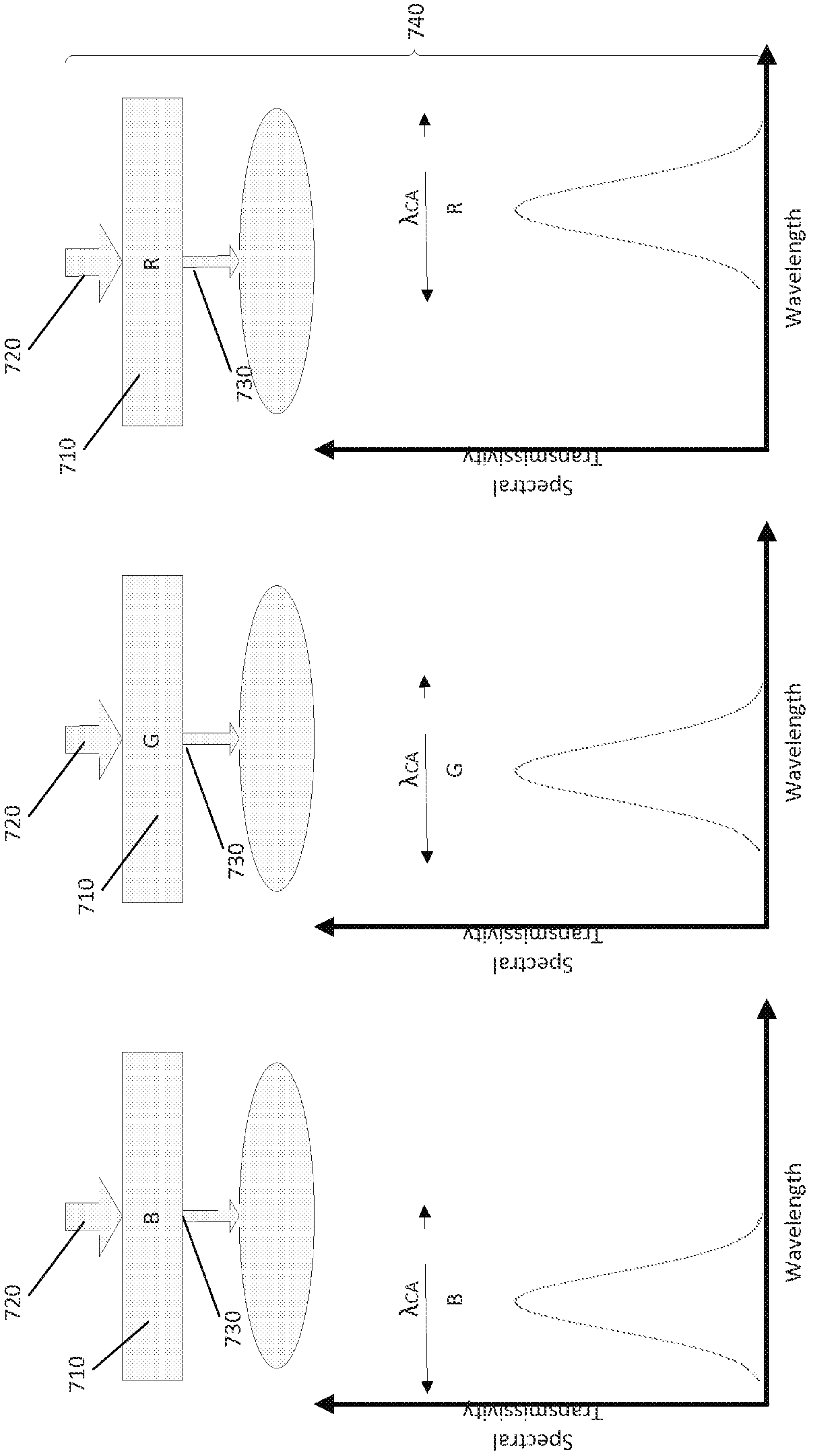
740
720
710
R
730
λCA
R
Spectral Transmissivity
Wavelength
720
710
G
730
λCA
G
Spectral Transmissivity
Wavelength
720
710
B
730
λCA
B
Spectral Transmissivity
Wavelength

FIG. 7

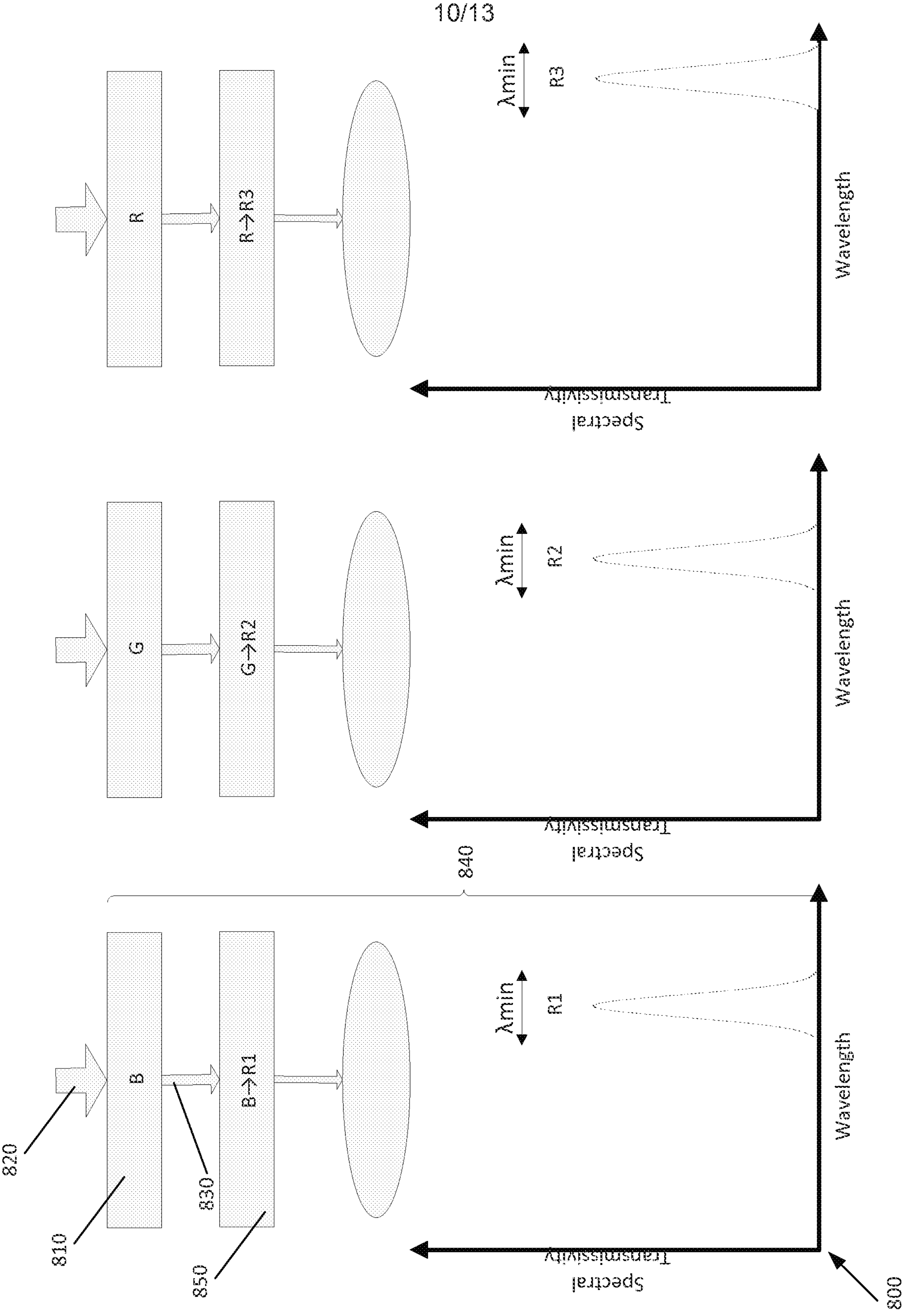
820
810
830
850
840
800
B
B→R1
G
G→R2
R
R→R3
λmin
R1
λmin
R2
λmin
R3
Spectral Transmissivity
Wavelength
Spectral Transmissivity
Wavelength
Spectral Transmissivity
Wavelength

FIG. 8

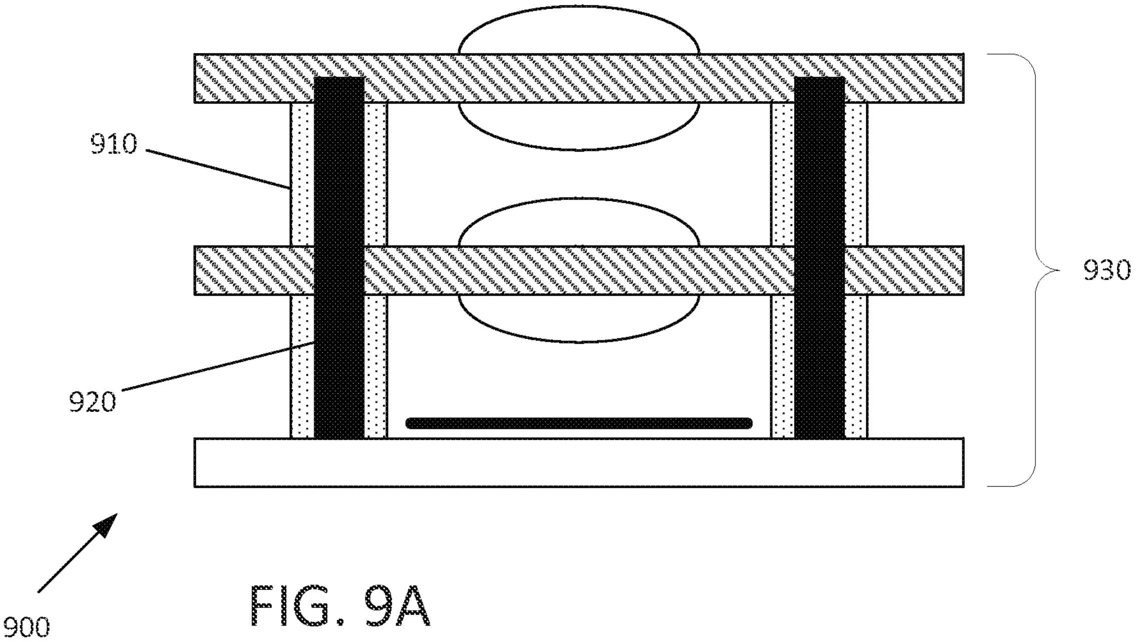

FIG. 9A

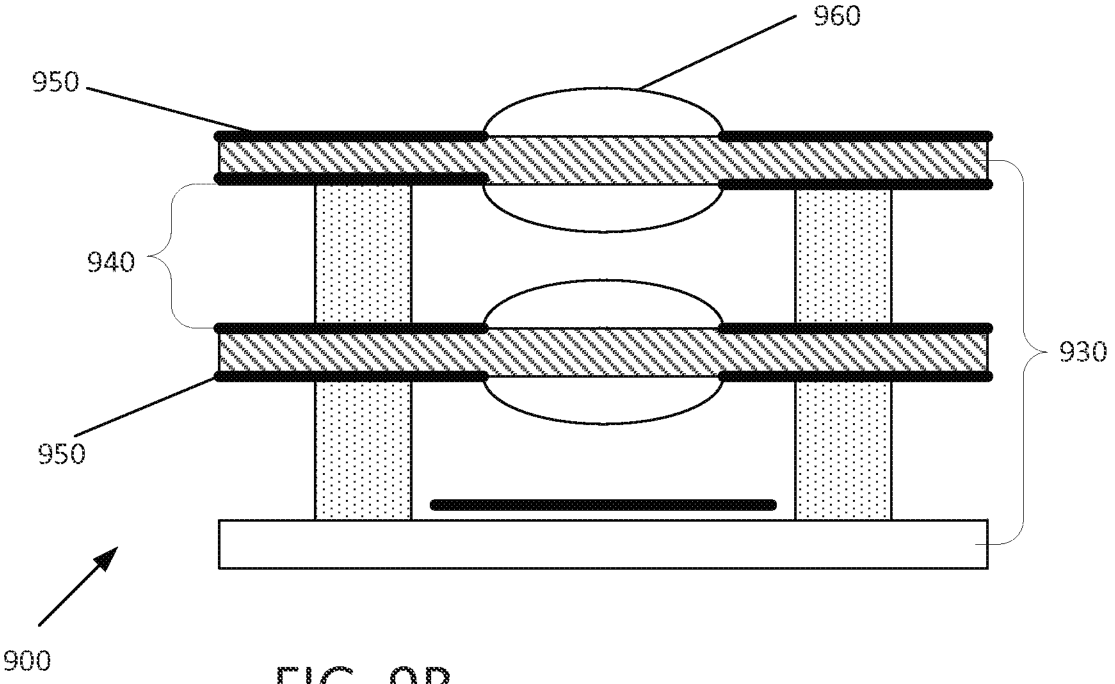

FIG. 9B

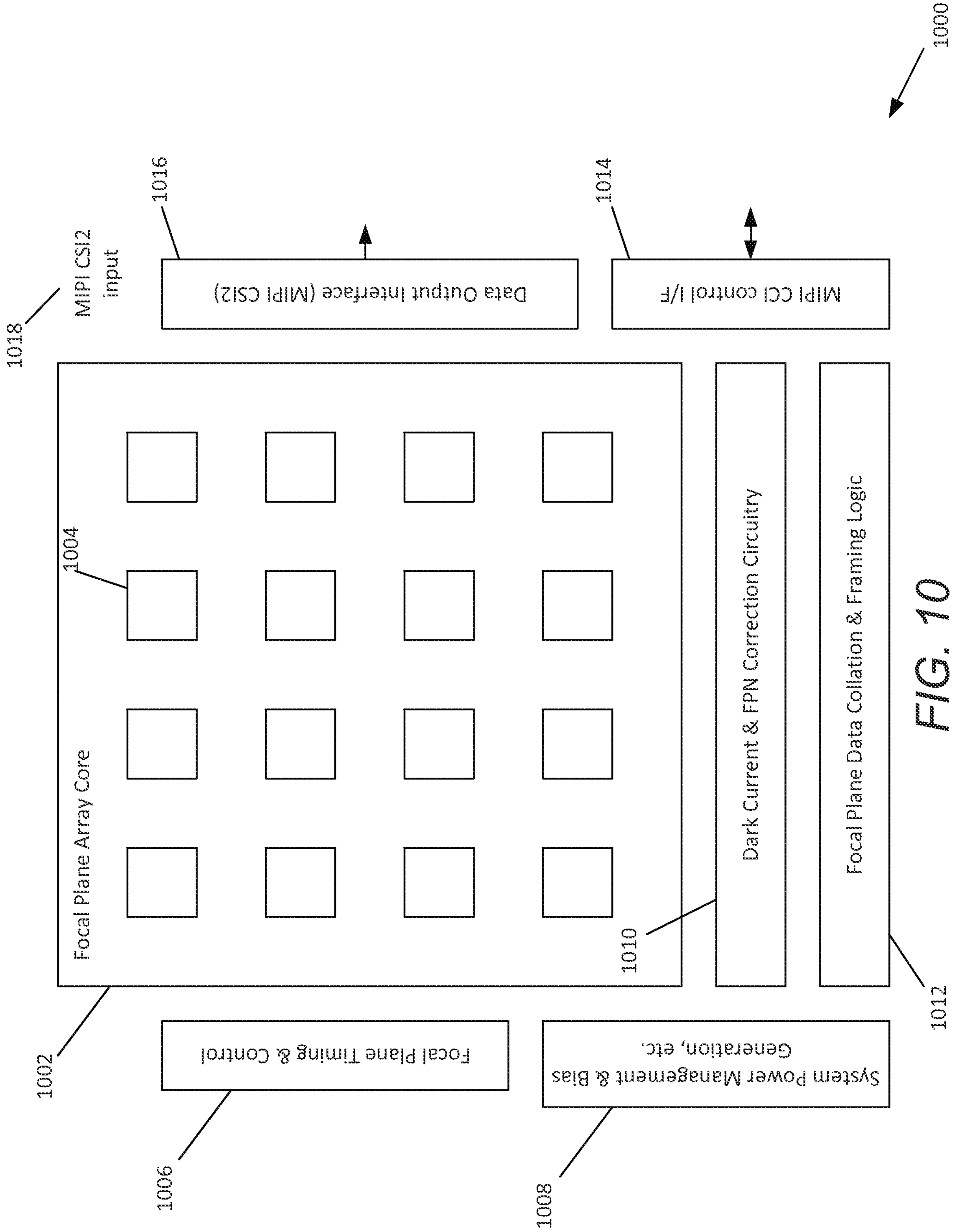
1000
1018
MIPI CSI2 input
1016
Data Output Interface (MIPI CSI2)
1014
MIPI CCI control I/F
Focal Plane Array Core
1004
Dark Current & FPN Correction Circuitry
Focal Plane Data Collation & Framing Logic
1010
1002
1012
Focal Plane Timing & Control
System Power Management & Bias Generation, etc.
1006
1008

FIG. 10

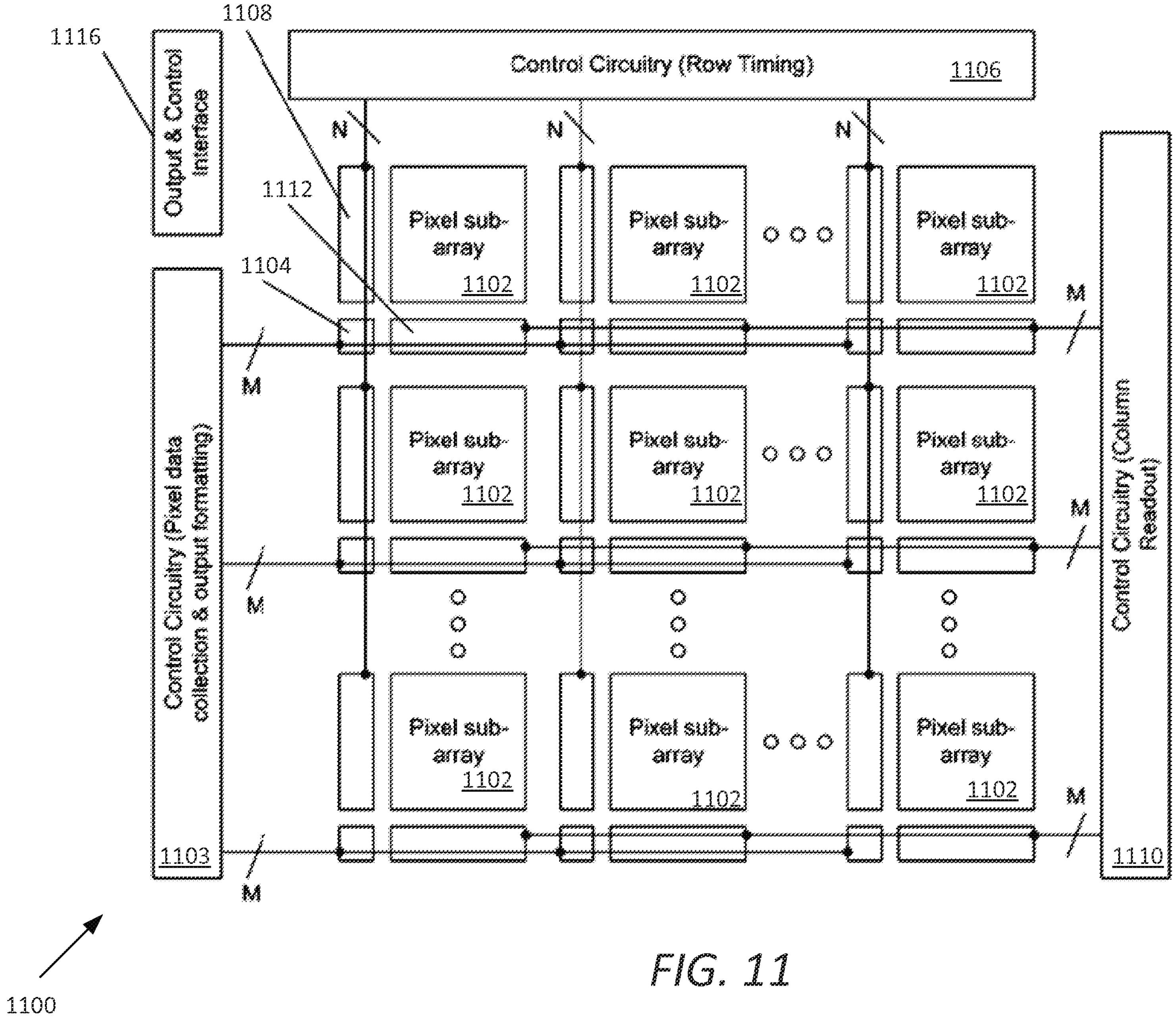
1116
1108
Output & Control Interface
Control Circuitry (Row Timing)
1106
1112
1104
N
N
N
Pixel sub-array
1102
M
Control Circuitry (Pixel data collection & output formatting)
1103
Control Circuitry (Column Readout)
1110
1100

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US14/24407

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G02B 5/20; H01L 29/06, 31/00 (2014.01)
USPC - 348/218.1; 250/226, 208.1
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) Classification(s): G02B 5/20, 27/10; H01L 29/06, 31/00 (2014.01)
USPC Classification(s): 348/218.1; 250/226, 208.1; 359/619; 257/13

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent (US-G, US-A, EP-A, EP-B, WO, JP-bib, DE-C,B, DE-A, DE-T, DE-U, GB-A, FR-A); Google Scholar; IP.COM; IEEE
Keywords used: lens stack array; optical channels; spectral filter; ultraviolet light; quantum dot color filter; array camera; imager array; focal planes; pixels; control circuitry; spacers; substrate; aperture; lens stacks; bandwidth; sampling circuitry

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2013/0003184 A1 (DUPARRE, J) January 03, 2013; abstract; figures 1-4; paragraphs [0010-0011]; [0017]; [0114-0115]; [0123-0126]	1-8
Y	US 7,986,018 B2 (RENNIE, J) July 26, 2011; figures 11A-B, 12; column 7, lines 5-33; column 8, lines 25-36; column 9, lines 49-57; column 10, lines 1-10; column 12, lines 39-57	1-8
Y	US 2012/0200734 A1 (TANG, S) August 09, 2012; figures 1-4; paragraphs [0017-0019]; [0049]; [0062]; [0067]; [0081]	3-4, 6, 8

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

* Special categories of cited documents:	"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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Date of the actual completion of the international search 11 June 2014 (11.06.2014)	Date of mailing of the international search report 08 JUL 2014
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774