



(51) International Patent Classification:

G02B 26/00 (2006.01) *G02F* 1/1335 (2006.01)
G02B 3/00 (2006.01) *H04N* 9/31 (2006.01)

(21) International Application Number:

PCT/US2015/034154

(22) International Filing Date:

4 June 2015 (04.06.2015)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

14/329,738 11 July 2014 (11.07.2014) US

(71) Applicant: **QUALCOMM MEMS TECHNOLOGIES, INC** [US/US]; 5775 Morehouse Drive, San Diego, California 92121-1714 (US).

(72) Inventors: **HONG, John Hyunchul**; 5775 Morehouse Drive, San Diego, California 92121-1714 (US). **MA, Jian Jim**; 5775 Morehouse Drive, San Diego, California 92121-1714 (US).

(74) Agents: **SAMPSON, Roger, S.** et al.; Weaver Austin Villeneuve & Sampson LLP, P.O. Box 70250, Oakland, California 94612-0250 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))

Published:

- with international search report (Art. 21(3))

(54) Title: MICROLENS COLOR SHIFT CONTROL

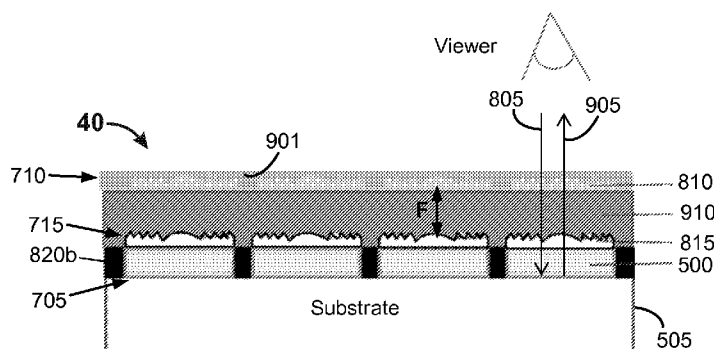


Figure 9A

(57) Abstract: Disclosed herein is a dual lens system capable of maintaining a substantially constant color within a well-defined angular range of light incident on a reflective pixel. Each reflective pixel (or subpixel) of a display may include a primary lens and a field lens. The field lens may be positioned at a distance equal to a focal length of the primary lens. Each plane wave of incident light arriving at the primary lens aperture may be focused on a unique location of the focal plane, but may emerge from the field lens within the same range of angles. If a reflective pixel is positioned below the field lens, the reflected color should be substantially the same within a range of viewing angles. The range of angles may be defined by the numerical aperture of the lens system and by black mask material disposed between the reflective pixels or subpixels. Thus, a reflective display includes an array of reflective pixels; an array of primary lenses, each of the primary lenses corresponding to a distinct one of the reflective pixels; and an array of field lenses, each of the field lenses corresponding to a distinct one of the reflective pixels and one of the primary lenses, each of the field lenses being positioned at a distance from a corresponding primary lens, the distance being a focal length of the corresponding primary lens, each of the field lenses being disposed proximate a corresponding reflective pixel.



MICROLENS COLOR SHIFT CONTROL

PRIORITY CLAIM

[0001] This application claims priority to United States Application No. 14/329,738,
5 filed on July 11, 2014 and entitled, "MICROLENS COLOR SHIFT CONTROL," which
is hereby incorporated by reference and for all purposes.

TECHNICAL FIELD

[0002] This disclosure relates to electromechanical systems and devices, and more
particularly to electromechanical systems for implementing reflective display devices.

10 DESCRIPTION OF THE RELATED TECHNOLOGY

[0003] Electromechanical systems (EMS) include devices having electrical and
mechanical elements, actuators, transducers, sensors, optical components such as
mirrors and optical films, and electronics. EMS devices or elements can be
manufactured at a variety of scales including, but not limited to, microscales and
15 nanoscales. For example, microelectromechanical systems (MEMS) devices can
include structures having sizes ranging from about a micron to hundreds of microns or
more. Nanoelectromechanical systems (NEMS) devices can include structures having
sizes smaller than a micron including, for example, sizes smaller than several hundred
nanometers. Electromechanical elements may be created using deposition, etching,
20 lithography, and/or other micromachining processes that etch away parts of substrates
and/or deposited material layers, or that add layers to form electrical and
electromechanical devices.

[0004] One type of EMS device is called an interferometric modulator (IMOD).
The term IMOD or interferometric light modulator refers to a device that selectively
25 absorbs and/or reflects light using the principles of optical interferometric absorption.
In some implementations, an IMOD display element may include a pair of conductive
plates, one of which has a high reflectance and one is partially absorptive. The pair of
conductive plates are capable of relative motion upon application of an appropriate
electrical signal. For example, one plate may include a stationary layer deposited over,
30 on or supported by a substrate and the other plate may include a partial absorptive

membrane separated from the stationary layer by an air gap. The position of one plate in relation to another can change the spectrum of the reflected light from the IMOD display element. IMOD-based display devices have a wide range of applications, and are anticipated to be used in improving existing products and creating new products, especially those with display capabilities.

[0005] Some IMODs are bi-stable IMODs, meaning that they can be configured in only two positions, high reflectance and low reflectance. At the high reflectance position, each pixel in a bi-stable IMOD reflects only one color, which may be a primary color. In some implementations, a display including such bi-stable IMODs may incorporate three sub-pixels to display an image pixel. In a display device that includes multi-state interferometric modulators (MS-IMODs) or analog IMODs (A-IMODs), each pixel can have more than two positions (or gap spacings), and a pixel's reflective color may be determined by the gap spacing or "gap height" between an absorber stack and a mirror stack of a single IMOD. As such, each pixel can reflect multiple colors. Some A-IMODs may be positioned in a substantially continuous manner between a large number of gap heights, whereas MS-IMODs may generally be positioned in a smaller number of gap heights.

SUMMARY

[0006] The systems, methods and devices of this disclosure each have several innovative aspects, no single one of which is solely responsible for the desirable attributes disclosed herein.

[0007] One innovative aspect of the subject matter described in this disclosure can be implemented in a reflective display. In some implementations, the reflective display may include an array of reflective pixels, an array of primary lenses and an array of field lenses. Each of the primary lenses may correspond to a distinct one of the reflective pixels. Each of the field lenses may correspond to a distinct one of the reflective pixels and one of the primary lenses. Each of the field lenses may be positioned at a distance from a corresponding primary lens. The distance may be a focal length of the corresponding primary lens.

[0008] In some implementations, each of the field lenses may be disposed proximate a corresponding reflective pixel. Light may be constrained by the primary lenses and the field lenses to be incident upon the reflective pixels within an angle

range. The angle range may be defined, at least in part, by an F-number of the primary lenses. Some implementations may include a diffuser layer disposed between the field lenses and the reflective pixels.

[0009] In some examples, the primary lenses and the field lenses may be diffractive optical elements. In some implementations, the primary lenses may be disposed within a photopolymer film.

[0010] Some implementations may include black mask material disposed between instances of the reflective pixels. According to some such implementations, the reflective pixels may be disposed in a first layer, the primary lenses may be disposed in a second layer and the black mask material may extend from the first layer to the second layer.

[0011] According to some such implementations, the array of reflective pixels may be disposed in a first layer, the primary lenses may be disposed in a second layer and the field lenses may be disposed in a third layer. In some examples, a fourth layer may be disposed between the second layer and the third layer. The black mask material may extend from the first layer at least partially into the fourth layer.

[0012] Some implementations may include a layer of low-index material disposed between the primary lenses and the field lenses. For example, the low-index material may have a refractive index that is lower than that of the primary lenses and the field lenses.

[0013] According to some implementations, the array of reflective pixels may include interferometric modulator (IMOD) pixels or reflective liquid crystal display (LCD) pixels. In some examples, a display device will include the reflective display. The display device may include a control system capable of controlling the display device and capable of processing image data. The control system may include a driver circuit capable of sending at least one signal to a display of the display device. The control system may include a controller capable of sending at least a portion of the image data to the driver circuit. The control system may include a processor and an image source module capable of sending the image data to the processor. The image source module may include a receiver, transceiver and/or a transmitter. The display device may include an input device capable of receiving input data and of communicating the input data to the control system.

[0014] Other innovative aspects of the subject matter described in this disclosure can be implemented in a reflective display. In some implementations, the reflective display may include apparatus for reflecting incident light and modulating reflected light. The reflecting and modulating apparatus may be disposed in a first layer. The reflective display may include apparatus for focusing incident light into a second layer proximate the first layer. The focusing apparatus may be disposed in a third layer.

[0015] The reflective display may include an array of field lenses disposed in the second layer. Each of the field lenses may correspond to instances of the reflecting and modulating apparatus, and may correspond to instances of the focusing apparatus. Each of the field lenses may be disposed proximate a corresponding instance of the reflecting and modulating apparatus. In some examples, the incident light may be constrained by the focusing apparatus and the array of field lenses to be incident upon the reflecting and modulating apparatus within an angle range.

[0016] In some implementations, the reflective display may include apparatus for masking light. The light-masking apparatus may, for example, be disposed between instances of the reflecting and modulating apparatus. The reflective display may include a fourth layer disposed between the second layer and the third layer. In some implementations, the light-masking apparatus may extend from the first layer at least partially into the fourth layer.

[0017] Other innovative aspects of the subject matter described in this disclosure can be implemented in a method of forming a reflective display. The method may involve forming an array of reflective pixels on a substrate and disposing an array of field lenses proximate the array of reflective pixels. Each of the field lenses may correspond to a distinct one of the reflective pixels. According to some examples, the method may involve disposing a diffuser layer between the field lenses and the reflective pixels.

[0018] The method may involve disposing a layer of low-index material proximate the array of field lenses. The low-index material may have a refractive index that is lower than that of the field lenses. In some implementations, the layer of low-index material may include optically clear resin and/or an optically clear adhesive.

[0019] The method may involve disposing an array of primary lenses on the layer of low-index material. In some examples, each of the primary lenses may correspond to a distinct one of the reflective pixels. Each of the primary lenses may be positioned at a

distance from a corresponding field lens. The distance may be a focal length of the primary lens.

[0020] In some implementations, the primary lenses and/or the field lenses may be diffractive optical elements. In some examples, the primary lenses may be disposed
5 within a photopolymer film.

[0021] According to some examples, the method may involve disposing black mask material between instances of the reflective pixels. In some implementations, disposing the black mask material may involve forming the black mask material at least partially into the layer of low-index material. In some examples, disposing the black mask
10 material may involve forming the black mask material from a first layer that includes the array of reflective pixels to a second layer that includes the array of primary lenses.

[0022] Details of one or more implementations of the subject matter described in this disclosure are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages will become apparent from the description, the
15 drawings and the claims. Note that the relative dimensions of the following figures may not be drawn to scale.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] Figure 1 is an isometric view illustration depicting two adjacent
20 interferometric modulator (IMOD) display elements in a series or array of display elements of an IMOD display device.

[0024] Figure 2 is a system block diagram illustrating an electronic device incorporating an IMOD-based display including a three element by three element array of IMOD display elements.

25 [0025] Figure 3 is a flow diagram illustrating a manufacturing process for an IMOD display or display element.

[0026] Figures 4A–4E are cross-sectional illustrations of various stages in a process of making an IMOD display or display element.

[0027] Figures 5A–5E show examples of how an IMOD may be configured to
30 produce different colors.

[0028] Figure 6A shows an example of an MS-IMOD being viewed along an axis that is substantially orthogonal to a surface of the mirror stack.

[0029] Figure 6B shows an example of an MS-IMOD being viewed along an axis that is at an angle α to the normal of the surface of the mirror stack.

[0030] Figure 7 is a block diagram that shows examples of elements of a reflective display.

5 [0031] Figure 8A shows an example of a primary lens and a field lens that may be used in a reflective display such as that shown in Figure 7.

[0032] Figure 8B shows an alternative example of elements that may be used in a reflective display such as that shown in Figure 7.

10 [0033] Figures 9A–9C provide examples implementing lens systems such as those shown in Figures 8A and 8B in a display device.

[0034] Figures 9D and 9E are graphs that indicate the wavelength shift according to viewing angle for examples of MS-IMOD displays with and without a lens system such as that disclosed herein.

15 [0035] Figure 10 is a flow diagram illustrating an example of a manufacturing process for a display.

[0036] Figures 11A and 11B are system block diagrams illustrating a display device 40 that includes a plurality of IMOD display elements.

[0037] Like reference numbers and designations in the various drawings indicate like elements.

20 DETAILED DESCRIPTION

[0038] The following description is directed to certain implementations for the purposes of describing the innovative aspects of this disclosure. However, a person having ordinary skill in the art will readily recognize that the teachings herein can be applied in a multitude of different ways. The described implementations may be
25 implemented in any device, apparatus, or system that can be configured to display an image, whether in motion (such as video) or stationary (such as still images), and whether textual, graphical or pictorial. More particularly, it is contemplated that the described implementations may be included in or associated with a variety of electronic devices such as, but not limited to: mobile telephones, multimedia Internet enabled
30 cellular telephones, mobile television receivers, wireless devices, smartphones, Bluetooth® devices, personal data assistants (PDAs), wireless electronic mail receivers, hand-held or portable computers, netbooks, notebooks, smartbooks, tablets, printers,

copiers, scanners, facsimile devices, global positioning system (GPS) receivers/navigators, cameras, digital media players (such as MP3 players), camcorders, game consoles, wrist watches, clocks, calculators, television monitors, flat panel displays, electronic reading devices (e.g., e-readers), computer monitors, auto displays
5 (including odometer and speedometer displays, etc.), cockpit controls and/or displays, camera view displays (such as the display of a rear view camera in a vehicle), electronic photographs, electronic billboards or signs, projectors, architectural structures, microwaves, refrigerators, stereo systems, cassette recorders or players, DVD players, CD players, VCRs, radios, portable memory chips, washers, dryers, washer/dryers,
10 parking meters, packaging (such as in electromechanical systems (EMS) applications including microelectromechanical systems (MEMS) applications, as well as non-EMS applications), aesthetic structures (such as display of images on a piece of jewelry or clothing) and a variety of EMS devices. The teachings herein also can be used in non-display applications such as, but not limited to, electronic switching devices, radio
15 frequency filters, sensors, accelerometers, gyroscopes, motion-sensing devices, magnetometers, inertial components for consumer electronics, parts of consumer electronics products, varactors, liquid crystal devices, electrophoretic devices, drive schemes, manufacturing processes and electronic test equipment. Thus, the teachings are not intended to be limited to the implementations depicted solely in the Figures, but
20 instead have wide applicability as will be readily apparent to one having ordinary skill in the art.

[0039] Various implementations disclosed herein include a dual lens system capable of maintaining a substantially constant color within a well-defined angle range, e.g., well-defined cone of light incident on a reflective pixel. In some implementations, each
25 reflective pixel (or subpixel) of a display may include a primary lens and a field lens. The field lens may be positioned at a distance equal to a focal length of the primary lens. Accordingly, each plane wave of incident light arriving at the primary lens aperture may be focused on a unique location of the focal plane, but may emerge from the field lens within a predetermined range (cone) of angles. The range of angles may
30 be defined by the F-number of the primary lens. The field lens provides an orientation of the cone normal to the display pixel and independent of the direction of the illumination light so long as the illumination is within the defined cone. If a reflective pixel is positioned below the field lens, the reflected color should be substantially the

same within a range of viewing angles. In some implementations, the range of angles may be defined, at least in part, by black mask material disposed between instances of the reflective pixels or subpixels.

[0040] Particular implementations of the subject matter described in this disclosure
5 can be implemented to realize one or more of the following potential advantages. The shift of the apparent color with changing view angle of some reflective display pixels, including interferometric modulator (IMOD) pixels and reflective liquid crystal display (LCD) pixels, is a well-known phenomenon. Implementations such as those disclosed herein can reduce the apparent color shift with viewing angle. Constraining the viewing
10 angle also may provide increased privacy for the user of such a display.

[0041] An example of a suitable EMS or MEMS device or apparatus, to which the described implementations may apply, is a reflective display device. Reflective display devices can incorporate interferometric modulator (IMOD) display elements that can be implemented to selectively absorb and/or reflect light incident thereon using principles
15 of optical interference. IMOD display elements can include a partial optical absorber, a reflector that is movable with respect to the absorber, and an optical resonant cavity defined between the absorber and the reflector. In some implementations, the reflector can be moved to two or more different positions, which can change the size of the optical resonant cavity and thereby affect the reflectance of the IMOD. The reflectance
20 spectra of IMOD display elements can create fairly broad spectral bands that can be shifted across the visible wavelengths to generate different colors. The position of the spectral band can be adjusted by changing the thickness of the optical resonant cavity. One way of changing the optical resonant cavity is by changing the position of the reflector with respect to the absorber.

[0042] Figure 1 is an isometric view illustration depicting two adjacent
25 interferometric modulator (IMOD) display elements in a series or array of display elements of an IMOD display device. The IMOD display device includes one or more interferometric EMS, such as MEMS, display elements. In these devices, the interferometric MEMS display elements can be configured in either a bright or dark state. In the bright (“relaxed,” “open” or “on,” etc.) state, the display element reflects a
30 large portion of incident visible light. Conversely, in the dark (“actuated,” “closed” or “off,” etc.) state, the display element reflects little incident visible light. MEMS display elements can be configured to reflect predominantly at particular wavelengths of light

allowing for a color display in addition to black and white. In some implementations, by using multiple display elements, different intensities of color primaries and shades of gray can be achieved.

[0043] The IMOD display device can include an array of IMOD display elements which may be arranged in rows and columns. Each display element in the array can include at least a pair of reflective and semi-reflective layers, such as a movable reflective layer (i.e., a movable layer, also referred to as a mechanical layer) and a fixed partially reflective layer (i.e., a stationary layer), positioned at a variable and controllable distance from each other to form an air gap (also referred to as an optical gap, cavity or optical resonant cavity). The movable reflective layer may be moved between at least two positions. For example, in a first position, i.e., a relaxed position, the movable reflective layer can be positioned at a distance from the fixed partially reflective layer. In a second position, i.e., an actuated position, the movable reflective layer can be positioned more closely to the partially reflective layer. Incident light that reflects from the two layers can interfere constructively and/or destructively depending on the position of the movable reflective layer and the wavelength(s) of the incident light, producing either an overall reflective or non-reflective state for each display element. In some implementations, the display element may be in a reflective state when unactuated, reflecting light within the visible spectrum, and may be in a dark state when actuated, absorbing and/or destructively interfering light within the visible range. In some other implementations, however, an IMOD display element may be in a dark state when unactuated, and in a reflective state when actuated. In some implementations, the introduction of an applied voltage can drive the display elements to change states. In some other implementations, an applied charge can drive the display elements to change states.

[0044] The depicted portion of the array in Figure 1 includes two adjacent interferometric MEMS display elements in the form of IMOD display elements 12. In the display element 12 on the right (as illustrated), the movable reflective layer 14 is illustrated in an actuated position near, adjacent or touching the optical stack 16. The voltage V_{bias} applied across the display element 12 on the right is sufficient to move and also maintain the movable reflective layer 14 in the actuated position. In the display element 12 on the left (as illustrated), a movable reflective layer 14 is illustrated in a relaxed position at a distance (which may be predetermined based on design parameters)

from an optical stack 16, which includes a partially reflective layer. The voltage V_0 applied across the display element 12 on the left is insufficient to cause actuation of the movable reflective layer 14 to an actuated position such as that of the display element 12 on the right.

5 [0045] In Figure 1, the reflective properties of IMOD display elements 12 are generally illustrated with arrows indicating light 13 incident upon the IMOD display elements 12, and light 15 reflecting from the display element 12 on the left. Most of the light 13 incident upon the display elements 12 may be transmitted through the transparent substrate 20, toward the optical stack 16. A portion of the light incident
10 upon the optical stack 16 may be transmitted through the partially reflective layer of the optical stack 16, and a portion will be reflected back through the transparent substrate 20. The portion of light 13 that is transmitted through the optical stack 16 may be reflected from the movable reflective layer 14, back toward (and through) the transparent substrate 20. Interference (constructive and/or destructive) between the
15 light reflected from the partially reflective layer of the optical stack 16 and the light reflected from the movable reflective layer 14 will determine in part the intensity of wavelength(s) of light 15 reflected from the display element 12 on the viewing or substrate side of the device. In some implementations, the transparent substrate 20 can be a glass substrate (sometimes referred to as a glass plate or panel). The glass substrate
20 may be or include, for example, a borosilicate glass, a soda lime glass, quartz, Pyrex, or other suitable glass material. In some implementations, the glass substrate may have a thickness of 0.3, 0.5 or 0.7 millimeters, although in some implementations the glass substrate can be thicker (such as tens of millimeters) or thinner (such as less than 0.3 millimeters). In some implementations, a non-glass substrate can be used, such as a
25 polycarbonate, acrylic, polyethylene terephthalate (PET) or polyether ether ketone (PEEK) substrate. In such an implementation, the non-glass substrate will likely have a thickness of less than 0.7 millimeters, although the substrate may be thicker depending on the design considerations. In some implementations, a non-transparent substrate, such as a metal foil or stainless steel-based substrate can be used. For example, a
30 reverse-IMOD-based display, which includes a fixed reflective layer and a movable layer which is partially transmissive and partially reflective, may be configured to be viewed from the opposite side of a substrate as the display elements 12 of Figure 1 and may be supported by a non-transparent substrate.

[0046] The optical stack 16 can include a single layer or several layers. The layer(s) can include one or more of an electrode layer, a partially reflective and partially transmissive layer, and a transparent dielectric layer. In some implementations, the optical stack 16 is electrically conductive, partially transparent and partially reflective, and may be fabricated, for example, by depositing one or more of the above layers onto a transparent substrate 20. The electrode layer can be formed from a variety of materials, such as various metals, for example indium tin oxide (ITO). The partially reflective layer can be formed from a variety of materials that are partially reflective, such as various metals (e.g., chromium and/or molybdenum), semiconductors, and dielectrics. The partially reflective layer can be formed of one or more layers of materials, and each of the layers can be formed of a single material or a combination of materials. In some implementations, certain portions of the optical stack 16 can include a single semi-transparent thickness of metal or semiconductor which serves as both a partial optical absorber and electrical conductor, while different, electrically more conductive layers or portions (e.g., of the optical stack 16 or of other structures of the display element) can serve to bus signals between IMOD display elements. The optical stack 16 also can include one or more insulating or dielectric layers covering one or more conductive layers or an electrically conductive/partially absorptive layer.

[0047] In some implementations, at least some of the layer(s) of the optical stack 16 can be patterned into parallel strips, and may form row electrodes in a display device as described further below. As will be understood by one having ordinary skill in the art, the term “patterned” is used herein to refer to masking as well as etching processes. In some implementations, a highly conductive and reflective material, such as aluminum (Al), may be used for the movable reflective layer 14, and these strips may form column electrodes in a display device. The movable reflective layer 14 may be formed as a series of parallel strips of a deposited metal layer or layers (orthogonal to the row electrodes of the optical stack 16) to form columns deposited on top of supports, such as the illustrated posts 18, and an intervening sacrificial material located between the posts 18. When the sacrificial material is etched away, a defined gap 19, or optical cavity, can be formed between the movable reflective layer 14 and the optical stack 16. In some implementations, the spacing between posts 18 may be approximately 1–1000 μm , while the gap 19 may be approximately less than 10,000 Angstroms ($\text{\AA}$).

[0048] In some implementations, each IMOD display element, whether in the actuated or relaxed state, can be considered as a capacitor formed by the fixed and moving reflective layers. When no voltage is applied, the movable reflective layer 14 remains in a mechanically relaxed state, as illustrated by the display element 12 on the left in Figure 1, with the gap 19 between the movable reflective layer 14 and optical stack 16. However, when a potential difference, i.e., a voltage, is applied to at least one of a selected row and column, the capacitor formed at the intersection of the row and column electrodes at the corresponding display element becomes charged, and electrostatic forces pull the electrodes together. If the applied voltage exceeds a threshold, the movable reflective layer 14 can deform and move near or against the optical stack 16. A dielectric layer (not shown) within the optical stack 16 may prevent shorting and control the separation distance between the layers 14 and 16, as illustrated by the actuated display element 12 on the right in Figure 1. The behavior can be the same regardless of the polarity of the applied potential difference. Though a series of display elements in an array may be referred to in some instances as “rows” or “columns,” a person having ordinary skill in the art will readily understand that referring to one direction as a “row” and another as a “column” is arbitrary. Restated, in some orientations, the rows can be considered columns, and the columns considered to be rows. In some implementations, the rows may be referred to as “common” lines and the columns may be referred to as “segment” lines, or vice versa. Furthermore, the display elements may be evenly arranged in orthogonal rows and columns (an “array”), or arranged in non-linear configurations, for example, having certain positional offsets with respect to one another (a “mosaic”). The terms “array” and “mosaic” may refer to either configuration. Thus, although the display is referred to as including an “array” or “mosaic,” the elements themselves need not be arranged orthogonally to one another, or disposed in an even distribution, in any instance, but may include arrangements having asymmetric shapes and unevenly distributed elements.

[0049] Figure 2 is a system block diagram illustrating an electronic device incorporating an IMOD-based display including a three element by three element array of IMOD display elements. The electronic device includes a processor 21 that may be configured to execute one or more software modules. In addition to executing an operating system, the processor 21 may be configured to execute one or more software

applications, including a web browser, a telephone application, an email program, or any other software application.

[0050] The processor 21 can be configured to communicate with an array driver 22. The array driver 22 can include a row driver circuit 24 and a column driver circuit 26 that provide signals to, for example a display array or panel 30. The cross section of the IMOD display device illustrated in Figure 1 is shown by the lines 1–1 in Figure 2. Although Figure 2 illustrates a 3x3 array of IMOD display elements for the sake of clarity, the display array 30 may contain a very large number of IMOD display elements, and may have a different number of IMOD display elements in rows than in columns, and vice versa.

[0051] Figure 3 is a flow diagram illustrating a manufacturing process 80 for an IMOD display or display element. Figures 4A–4E are cross-sectional illustrations of various stages in the manufacturing process 80 for making an IMOD display or display element. In some implementations, the manufacturing process 80 can be implemented to manufacture one or more EMS devices, such as IMOD displays or display elements. The manufacture of such an EMS device also can include other blocks not shown in Figure 3. The process 80 begins at block 82 with the formation of the optical stack 16 over the substrate 20. Figure 4A illustrates such an optical stack 16 formed over the substrate 20. The substrate 20 may be a transparent substrate such as glass or plastic such as the materials discussed above with respect to Figure 1. The substrate 20 may be flexible or relatively stiff and unbending, and may have been subjected to prior preparation processes, such as cleaning, to facilitate efficient formation of the optical stack 16. As discussed above, the optical stack 16 can be electrically conductive, partially transparent, partially reflective, and partially absorptive, and may be fabricated, for example, by depositing one or more layers having the desired properties onto the transparent substrate 20.

[0052] In Figure 4A, the optical stack 16 includes a multilayer structure having sub-layers 16a and 16b, although more or fewer sub-layers may be included in some other implementations. In some implementations, one of the sub-layers 16a and 16b can be configured with both optically absorptive and electrically conductive properties, such as the combined conductor/absorber sub-layer 16a. In some implementations, one of the sub-layers 16a and 16b can include molybdenum-chromium (molychrome or MoCr), or other materials with a suitable complex refractive index. Additionally, one or more of

the sub-layers 16a and 16b can be patterned into parallel strips, and may form row electrodes in a display device. Such patterning can be performed by a masking and etching process or another suitable process known in the art. In some implementations, one of the sub-layers 16a and 16b can be an insulating or dielectric layer, such as an upper sub-layer 16b that is deposited over one or more underlying metal and/or oxide layers (such as one or more reflective and/or conductive layers). In addition, the optical stack 16 can be patterned into individual and parallel strips that form the rows of the display. In some implementations, at least one of the sub-layers of the optical stack, such as the optically absorptive layer, may be quite thin (e.g., relative to other layers depicted in this disclosure), even though the sub-layers 16a and 16b are shown somewhat thick in Figures 4A–4E.

[0053] The process 80 continues at block 84 with the formation of a sacrificial layer 25 over the optical stack 16. Because the sacrificial layer 25 is later removed (see block 90) to form the cavity 19, the sacrificial layer 25 is not shown in the resulting IMOD display elements. Figure 4B illustrates a partially fabricated device including a sacrificial layer 25 formed over the optical stack 16. The formation of the sacrificial layer 25 over the optical stack 16 may include deposition of a xenon difluoride (XeF_2)-etchable material such as molybdenum (Mo) or amorphous silicon (Si), in a thickness selected to provide, after subsequent removal, a gap or cavity 19 (see also Figure 4E) having a desired design size. Deposition of the sacrificial material may be carried out using deposition techniques such as physical vapor deposition (PVD, which includes many different techniques, such as sputtering), plasma-enhanced chemical vapor deposition (PECVD), thermal chemical vapor deposition (thermal CVD), or spin-coating.

[0054] The process 80 continues at block 86 with the formation of a support structure such as a support post 18. The formation of the support post 18 may include patterning the sacrificial layer 25 to form a support structure aperture, then depositing a material (such as a polymer or an inorganic material, like silicon oxide) into the aperture to form the support post 18, using a deposition method such as PVD, PECVD, thermal CVD, or spin-coating. In some implementations, the support structure aperture formed in the sacrificial layer can extend through both the sacrificial layer 25 and the optical stack 16 to the underlying substrate 20, so that the lower end of the support post 18 contacts the substrate 20. Alternatively, as depicted in Figure 4C, the aperture formed

in the sacrificial layer 25 can extend through the sacrificial layer 25, but not through the optical stack 16. For example, Figure 4E illustrates the lower ends of the support posts 18 in contact with an upper surface of the optical stack 16. The support post 18, or other support structures, may be formed by depositing a layer of support structure material over the sacrificial layer 25 and patterning portions of the support structure material located away from apertures in the sacrificial layer 25. The support structures may be located within the apertures, as illustrated in Figure 4C, but also can extend at least partially over a portion of the sacrificial layer 25. As noted above, the patterning of the sacrificial layer 25 and/or the support posts 18 can be performed by a masking and etching process, but also may be performed by alternative patterning methods.

[0055] The process 80 continues at block 88 with the formation of a movable reflective layer or membrane such as the movable reflective layer 14 illustrated in Figure 44. The movable reflective layer 14 may be formed by employing one or more deposition steps, including, for example, reflective layer (such as aluminum, aluminum alloy, or other reflective materials) deposition, along with one or more patterning, masking and/or etching steps. The movable reflective layer 14 can be patterned into individual and parallel strips that form, for example, the columns of the display. The movable reflective layer 14 can be electrically conductive, and referred to as an electrically conductive layer. In some implementations, the movable reflective layer 14 may include a plurality of sub-layers 14a, 14b and 14c as shown in Figure 4D. In some implementations, one or more of the sub-layers, such as sub-layers 14a and 14c, may include highly reflective sub-layers selected for their optical properties, and another sub-layer 14b may include a mechanical sub-layer selected for its mechanical properties. In some implementations, the mechanical sub-layer may include a dielectric material. Since the sacrificial layer 25 is still present in the partially fabricated IMOD display element formed at block 88, the movable reflective layer 14 is typically not movable at this stage. A partially fabricated IMOD display element that contains a sacrificial layer 25 also may be referred to herein as an “unreleased” IMOD.

[0056] The process 80 continues at block 90 with the formation of a cavity 19. The cavity 19 may be formed by exposing the sacrificial material 25 (deposited at block 84) to an etchant. For example, an etchable sacrificial material such as Mo or amorphous Si may be removed by dry chemical etching by exposing the sacrificial layer 25 to a gaseous or vaporous etchant, such as vapors derived from solid XeF_2 for a period of

time that is effective to remove the desired amount of material. The sacrificial material is typically selectively removed relative to the structures surrounding the cavity 19. Other etching methods, such as wet etching and/or plasma etching, also may be used. Since the sacrificial layer 25 is removed during block 90, the movable reflective layer 14 is typically movable after this stage. After removal of the sacrificial material 25, the resulting fully or partially fabricated IMOD display element may be referred to herein as a “released” IMOD.

[0057] In some implementations, the packaging of an EMS component or device, such as an IMOD-based display, can include a backplate (alternatively referred to as a backplane, back glass or recessed glass) which can be configured to protect the EMS components from damage (such as from mechanical interference or potentially damaging substances). The backplate also can provide structural support for a wide range of components, including but not limited to driver circuitry, processors, memory, interconnect arrays, vapor barriers, product housing, and the like. In some implementations, the use of a backplate can facilitate integration of components and thereby reduce the volume, weight, and/or manufacturing costs of a portable electronic device.

[0058] Figures 5A–5E show examples of how a single IMOD (IMOD) may be configured to produce different colors. Multistate IMODs (MS-IMODs) and analog IMODs (A-IMODs) are both considered to be examples of the broader class of IMODs.

[0059] In an MS-IMOD, a pixel’s reflective color may be varied by changing the gap height between an absorber stack and a mirror stack. In Figures 5A–5E, the IMOD 500 includes the mirror stack 505 and the absorber stack 510. In this implementation, the absorber stack 510 is partially reflective and partially absorptive. Here, the mirror stack 505 includes at least one metallic reflective layer, which also may be referred to herein as a mirrored surface or a metal mirror.

[0060] In some implementations, the absorber layer may be formed of a partially absorptive and partially reflective layer. The absorber layer may be part of an absorber stack that includes other layers, such as one or more dielectric layers, an electrode layer, etc. According to some such implementations, the absorber stack may include a dielectric layer, a metal layer and a passivation layer. In some implementations, the dielectric layer may be formed of SiO₂, SiON, MgF₂, Al₂O₃ and/or other dielectric materials. In some implementations, the metal layer may be formed of Cr, W, Ni, V, Ti,

Rh, Pt, Ge, Co and/or MoCr. In some implementations, the passivation layer may include Al_2O_3 or another dielectric material.

[0061] The mirror may, for example, be formed of one or more reflective metals such as Al, silver, etc. In some MS-IMODs, the mirror may be part of a mirror stack
5 that includes other layers, such as one or more dielectric layers. Such dielectric layers may be formed of TiO_2 , Si_3N_4 , ZrO_2 , Ta_2O_5 , Sb_2O_3 , HfO_2 , Sc_2O_3 , In_2O_3 , $\text{Sn}:\text{In}_2\text{O}_3$, SiO_2 , SiON , MgF_2 , Al_2O_3 , HfF_4 , YbF_3 , Na_3AlF_6 and/or other dielectric materials.

[0062] In Figures 5A–5E, the mirror stack 505 is shown at five positions relative to the absorber stack 510. However, an IMOD 500 may be movable between substantially
10 more than 5 positions relative to the mirror stack 505. For example, in some A-IMOD implementations, the gap height 530 between the mirror stack 505 and the absorber stack 510 may be varied in a substantially continuous manner. In some such IMODs 500, the gap height 530 may be controlled with a high level of precision, e.g., with an error of 10 nanometers (nm) or less. Although the absorber stack 510 includes a single
15 absorber layer in this example, alternative implementations of the absorber stack 510 may include multiple absorber layers. Moreover, in alternative implementations, the absorber stack 510 may not be partially reflective.

[0063] An incident wave having a wavelength λ will interfere with its own reflection from the mirror stack 505 to create a standing wave with local peaks and
20 nulls. The first null is $\lambda/2$ from the mirror and subsequent nulls are located at $\lambda/2$ intervals. For that wavelength, a thin absorber layer placed at one of the null positions will absorb very little energy.

[0064] Referring first to Figure 5A, when the gap height 530 is substantially equal to the half wavelength of a red wavelength of light 525 (also referred to herein as a red
25 color), the absorber stack 510 is positioned at the null of the red standing wave interference pattern. The absorption of the red wavelength of light 525 is near zero because there is almost no red light at the absorber. At this configuration, constructive interference appears between red wavelengths of light reflected from the absorber stack 510 and red wavelengths of light reflected from the mirror stack 505. Therefore, light
30 having a wavelength substantially corresponding to the red wavelength of light 525 is reflected efficiently. Light of other colors, including the blue wavelength of light 515 and the green wavelength of light 520, has a high intensity field at the absorber and is

not reinforced by constructive interference. Instead, such light is substantially absorbed by the absorber stack 510.

[0065] Figure 5B depicts the IMOD 500 in a configuration wherein the mirror stack 505 is moved closer to the absorber stack 510 (or vice versa). In this example, the gap height 530 is substantially equal to the half wavelength of the green wavelength of light 520. The absorber stack 510 is positioned at the null of the green standing wave interference pattern. The absorption of the green wavelength of light 520 is near zero because there is almost no green light at the absorber. At this configuration, constructive interference appears between green light reflected from the absorber stack 510 and green light reflected from the mirror stack 505. Light having a wavelength substantially corresponding to the green wavelength of light 520 is reflected efficiently. Light of other colors, including the red wavelength of light 525 and the blue wavelength of light 515, is substantially absorbed by the absorber stack 510.

[0066] In Figure 5C, the mirror stack 505 is moved closer to the absorber stack 510 (or vice versa), so that the gap height 530 is substantially equal to the half wavelength of the blue wavelength of light 515. Light having a wavelength substantially corresponding to the blue wavelength of light 515 is reflected efficiently. Light of other colors, including the red wavelength of light 525 and the green wavelength of light 520, is substantially absorbed by the absorber stack 510.

[0067] In Figure 5D, however, the IMOD 500 is in a configuration wherein the gap height 530 is substantially equal to $\frac{1}{4}$ of the wavelength of the average color in the visible range. In such arrangement, the absorber is located near the intensity peak of the interference standing wave; the strong absorption due to high field intensity together with destructive interference between the absorber stack 510 and the mirror stack 505 causes relatively little visible light to be reflected from the IMOD 500. This configuration may be referred to herein as a “black state.” In some such implementations, the gap height 530 may be made larger or smaller than shown in Figure 5D, in order to reinforce other wavelengths that are outside the visible range. Accordingly, the configuration of the IMOD 500 shown in Figure 5D provides merely one example of a black state configuration of the IMOD 500.

[0068] Figure 5E depicts the IMOD 500 in a configuration wherein the absorber stack 510 is in close proximity to the mirror stack 505. In this example, the gap height 530 is negligible because the absorber stack 510 is substantially adjacent to the mirror

stack 505. Light having a broad range of wavelengths is reflected efficiently from the mirror stack 505 without being absorbed to a significant degree by the absorber stack 510. This configuration may be referred to herein as a “white state.” However, in some implementations the absorber stack 510 and the mirror stack 505 may be separated to
5 reduce stiction caused by charging via the strong electric field that may be produced when the two layers are brought close to one another. In some implementations, one or more dielectric layers with a total thickness of about $\lambda/2$ may be disposed on the surface of the absorber layer and/or the mirrored surface. As such, the white state may correspond to a configuration wherein the absorber layer is placed at the first null of the
10 standing wave from the mirrored surface of the mirror stack 505.

[0069] The shift of the apparent color with changing view angle of some reflective display pixels, including IMOD pixels and reflective liquid crystal display (LCD) pixels, is a well-known phenomenon. The blue shift in the reflection spectrum with changing view angle has been a characteristic of previously-disclosed interferometric
15 devices that employ a layered structure, including IMODs. Cholesteric LCD pixels provide a particularly significant color shift as the viewing angle changes.

[0070] Figure 6A shows an example of an MS-IMOD being viewed along an axis that is substantially orthogonal to a surface of the mirror stack. Light incident normal to the mirror stack 505 creates standing wave interference patterns that begin with a zero
20 energy null at the mirror surface and periodically repeat away from the mirror. The null locations repeat every half wavelength. Therefore, the distance between null locations depends on the wavelength of each of the spectral components of light.

[0071] Figure 6A shows examples of a standing wave interference pattern for red wavelengths of light 605a, a standing wave interference pattern for green wavelengths of light 610 and a standing wave interference pattern for blue wavelengths of light 615.
25 The nulls are depicted as the darkest areas of the standing wave interference patterns and the peaks are depicted as the brightest areas of the standing wave interference patterns. Because the red wavelengths of light 525 have the longest wavelengths, the distance between null locations for the red wavelengths of light 525 is greater than that
30 for the green wavelengths of light 520 or the blue wavelengths of light 515.

[0072] In the examples shown in Figure 6A, the absorber stack 510 is positioned at a null of the standing wave interference pattern for red wavelengths of light 605a. The observer 620 is viewing light that is traveling along an axis that is substantially normal

to the surface of the mirror stack. The absorber stack 510 causes the light to be absorbed unless the spectral component has a null location at the absorber position, in which case little or no energy is absorbed and the light is reflected with high efficiency.

[0073] Therefore, when the MS-IMOD 500 is in the configuration shown in Figure 6A, the observer 620 can perceive red wavelengths of light 525 reflected from the mirror stack 505. Light of other colors, including the blue wavelengths of light 515 and the green wavelengths of light 520, has a higher intensity field at the absorber location and is substantially absorbed by the absorber stack 510.

[0074] Figure 6B shows an example of an MS-IMOD being viewed along an axis that is at an angle α to the normal of the surface of the mirror stack. The absorber stack 510 is in the same position shown in Figure 6A. However, while this position of the absorber stack 510 yields a red reflection for normal-incidence viewing, off-axis viewing causes the fringes to stretch by an inverse cosine factor due to the increased distance traveled by the incident and reflected light. This increase in distance causes a shift of the null location, as shown in the standing wave interference pattern for red wavelengths of light 605b, causing some incident red wavelengths of light 525 to be absorbed.

[0075] However, a shorter wavelength component at the same incidence angle α has a zero energy null coincident with the same absorber position and thus reflects with high efficiency. This is shown by the standing wave interference pattern for orange wavelengths of light 625. The result is an apparent shift in color (towards the blue range) for the same gap 530 when the observer 620 views the MS-IMOD 500 from an off-axis position. Similar effects are produced when the MS-IMOD 500 is configured for reflecting green, blue or other colors and viewed off-axis.

[0076] Some implementations disclosed herein include a dual lens system capable of maintaining a substantially constant color within a defined angular range of light incident on a reflective pixel. In some implementations, each reflective pixel (or subpixel) of a display may include a primary lens and a field lens. Various examples are described below with reference to Figures 7 *et. seq.*

[0077] Figure 7 is a block diagram that shows examples of elements of a reflective display. In this example, the display device 40 includes an array of reflective pixels 705, an array of primary lenses 710 and an array of field lenses 715. In some implementations, each of the primary lenses corresponds to a distinct one of the

reflective pixels, which also may be referred to herein as an “instance” of the reflective pixels.

[0078] Each of the field lenses also may correspond to a distinct one of the reflective pixels and one of the primary lenses. Each of the field lenses may be disposed proximate a corresponding reflective pixel. Each of the field lenses may be positioned at a distance from a corresponding primary lens. The distance may be a focal length of the corresponding primary lens. The focal length of the field lens may be identical, or substantially identical, to the focal length of the primary lens.

[0079] Figure 8A shows an example of a primary lens and a field lens that may be used in a reflective display such as that shown in Figure 7. In Figure 8A, plane waves of incident light 805a and 805b are shown arriving at the primary lens. The solid lines represent the chief rays corresponding to the incident light 805a and 805b, and the dashed lines represent marginal rays. Only a half width of each beam is shown.

[0080] Here, the primary lens 810 has a width W that may substantially correspond with a width of an underlying reflective pixel, which is not shown in Figure 8A. The primary lens 810 focuses incident light, including the incident light 805a and 805b, on various locations of the focal plane, one focal length (F) away. A field lens 815 is positioned in the focal plane. In this example, the field lens 815 has the same focal length as the primary lens 810.

[0081] The combined effect of the primary lens 810 and the field lens 815 is that each plane wave of incident light arriving at the primary lens 810 ends up at a unique location at the focal plane of the primary lens 810, but emerges from the field lens 815 within the same range of angles (also referred to herein as an exit cone). This range of angles is shown as $\Delta\theta_{\text{exit}}$ in Figure 8A. This angle range is achieved by the primary lens. In this example, the orientation of the exit cone is parallel to the optical axis and independent of the incident wave angle. This effect is achieved by the field lens. If both the range of angles $\Delta\theta_{\text{exit}}$ and the orientation of the cone are independent of the illumination wave angle, the reflected color from a reflective pixel positioned below the field lens 815 should be substantially the same within a range of viewing angles

[0082] In some implementations, the range of angles $\Delta\theta_{\text{exit}}$ may be based, at least in part, on the F-number of the primary lens 810. In this example, the range of angles emerging from the field lens is given by:

$$\Delta\theta_{exit} = 2\tan^{-1}\left(\frac{W}{2F}\right) = 2\tan^{-1}\left(\frac{1}{2F\#}\right) \quad (\text{Equation 1})$$

[0083] In Equation 1, W represents the entrance pupil diameter of the primary lens 810, F represents the focal length of the primary lens 810 and F# represents the F-number or focal ratio of the primary lens 810.

5 [0084] The angle range of the incident light 805a and 805b (also referred to herein as the entrance cone) is equal to the angle range of the exit cone $\Delta\theta_{exit}$ in this symmetrical example, in which the apertures of the primary lens 810 and the field lens 815 are the same. However, in other implementations the apertures and/or the angle ranges of the primary lens 810 and the field lens 815 may not be the same. For
10 example, in some instances the angle range of incident light may exceed the angle range of the exit cone. In such instances, light entering outside of the entrance cone would not be captured by the field lens. An illumination ray angle outside of this angle range will leak from the primary lens to the neighboring field lens, and be color shifted. Accordingly, some implementations may include additional apparatus for controlling
15 incident light angles and/or intensity, such as vignetting apertures, black mask material, etc.

[0085] A large exit angle range may introduce color desaturation because the color of reflected wave is a mixture of rays reflected at different angles each has a color angle shift. By reducing the exit angle, color desaturation and ray crosstalk between the
20 neighboring primary lens/field lens pairs can be minimized. Figure 8B shows an alternative example of elements that may be used in a reflective display such as that shown in Figure 7. In this example, the aperture of the field lens 815 is restricted by black mask (BM) material 820a, which constrains the viewing angle range (shown as $\Delta\theta_{view}$ in Figure 8B). This constraint on viewing angle range $\Delta\theta_{view}$ can have various
25 potential benefits, for example, reducing the amount of color shift and color desaturation. Constraining the viewing angle range also can provide increased privacy for a user of a display, because the decreased range of viewing angles reduces the angle range within which third parties may be able to view what is rendered on the display.

[0086] In the implementation shown in Figure 8B, a diffuser 825 is disposed
30 between the field lens 815 and a reflective display pixel, which is an MS-IMOD 500 in this example. The color reflected from the MS-IMOD 500 may be substantially the same within the viewing angle range $\Delta\theta_{view}$. In alternative examples, the black mask material may be positioned as shown by the dashed outline of black mask material

820b, or may include the areas outlined by both elements 820a and 820b. In such implementations, the black mask material 820b may be disposed, at least in part, in a layer that includes the reflective pixels of a display.

[0087] Figures 9A–9C provide examples implementing lens systems such as those shown in Figures 8A and 8B in a display device. Referring first to Figure 9A, in this example, the display device 40 includes an array of reflective pixels 705, an array of primary lenses 710 and an array of field lenses 715. In this example, the primary lenses 810 are diffractive optical elements formed within a layer 901, which is a photopolymer film in this example.

[0088] In this implementation, the field lenses 815 also are diffractive optical elements, each of which is disposed proximate a corresponding reflective pixel of the array of reflective pixels 705. However, in alternative implementations, the primary lenses 810 and/or the field lenses 815 may be other types of lenses, such as refractive lenses shown in Figures 8A and 8B. Here, each of the field lenses 815 is positioned at a distance F from a corresponding primary lens 810, where F is a focal length of the primary lens 810. Some implementations may include a diffuser positioned between each field lens 815 and each corresponding reflective pixel, e.g., as shown in Figure 8B.

[0089] In this example, a layer 910 is disposed between the array of primary lenses 710 and the array of field lenses 715. In this implementation the layer 910 includes a low-index material having a lower index of refraction than that of the primary lenses 810 or the field lenses 815. For example, the low-index material may include an optically clear resin (OCR) or an optically clear adhesive (OCA).

[0090] In this example, the reflective pixels are MS-IMODs 500. However, other implementations may include different types of reflective pixels, such as reflective LCD pixels.

[0091] In this example, incident light 805 may enter the display device 40 from the side that includes the array of primary lenses 710. Incident light 805 may be focused in a plane that includes the array of field lenses 715, e.g., as described above with reference to Figure 8A. Accordingly, the incident light 805 may be constrained by the primary lenses 810 and the field lenses 815 to be incident upon the MS-IMODs 500 within a predetermined angle range. Reflected light 905 may be modulated by the MS-IMODs 500 as described above. Accordingly, the MS-IMODs 500 include apparatus for reflecting incident light and modulating reflected light.

[0092] As shown in Figure 9A, in this example the display device 40 is configured to be viewed through the layer 901, not through the substrate 505 on which the reflective pixels are formed. Accordingly, in this example the substrate 505 does not need to be transparent. For example, MS-IMODs 500 may include a mirror that is disposed between an absorber layer and the substrate 505.

[0093] In this example, black mask material 820b is disposed between instances of the reflective pixels. In some examples, the black mask may extend part or all the way to the photopolymer film. In some such examples, the black mask may surround each of the reflective pixels, isolating each pixel from stray light that may enter above neighboring reflective pixels.

[0094] In the implementation of display device 40 shown in Figure 9B, for example, the array of reflective pixels 705 is disposed in a first layer, the primary lenses 810 are disposed in a second layer (the layer 901), the field lenses 815 are disposed in a third layer, a fourth layer (the layer 910) is disposed between the second layer and the third layer, and the black mask material 820c extends from the first layer at least partially into the fourth layer. In the implementation of display device 40 shown in Figure 9C, the reflective pixels (MS-IMODs 500) are disposed in a first layer, the primary lenses 810 are disposed in a second layer (the layer 901), and the black mask material 820d extends from the first layer to the second layer.

[0095] As described above, the field lenses 815 may be positioned at a distance equal to a focal length of the primary lenses 810. Accordingly, each plane wave of incident light 805 arriving at the primary lens aperture may be focused on a unique location of the focal plane (the plane in which the field lenses 815 are disposed), but may emerge from the field lens 815 within a predetermined range of angles. The range of angles may be defined by the F-number of the primary lens 810. In some implementations, such as those shown in Figures 9B and 9C, the range of angles may be defined, at least in part, by black mask material disposed between instances of the reflective pixels.

[0096] Figures 9D and 9E are graphs that indicate the wavelength shift according to viewing angle for examples of MS-IMOD displays with and without a lens system such as that disclosed herein. The graph shown in Figure 9D indicates the response of an MS-IMOD with such a lens system and the graph shown in Figure 9E indicates the response of an MS-IMOD without such a lens system. In both examples, the MS-

IMOD was maintained in the same position throughout the indicated viewing angle range. The same type of diffused incident light was used for illuminating the MS-IMOD in both examples.

[0097] Here, the graph shown in Figure 9D indicates substantially no wavelength shift with viewing angle. However, the graph shown in Figure 9E indicates a wavelength shift with viewing angle: Figure 9E indicates a “blue shift,” towards, the shorter end of the range of visible wavelengths.

[0098] In alternative implementations, the primary lens 810 and the field lens 815 of display device 40 may be replaced by a single gradient index (GRIN) lens for to each reflective pixel or subpixel of a display. The GRIN lens may be designed so as to give rise to a quarter pitch which maps an input angle to a focused spot at the exit pupil. The exit cone angle may be defined, at least in part, by the numerical aperture of the GRIN lens. The field lens may not be necessary with the use of GRIN lens as the primary lens because the exit light cone orientation is not sensitive to the input wave angle.

[0099] Figure 10 is a flow diagram illustrating an example of a manufacturing process for a display. In this example, the method 1000 begins with block 1005, which involves forming an array of reflective pixels (or subpixels) on a substrate. In some implementations, block 1005 may involve forming an array of reflective IMOD pixels, such as MS-IMOD pixels. For example, block 1005 may involve forming an array of reflective “reverse IMOD” pixels (or subpixels), as described elsewhere herein. In other implementations, block 1005 may involve forming an array of reflective LCD pixels (or subpixels).

[0100] Here, block 1010 involves disposing an array of field lenses proximate the array of reflective pixels. Each of the field lenses may correspond to a distinct one of the reflective pixels. For example, block 1010 may involve disposing a film that includes a plurality of field lenses, such as diffractive optical elements, on the array of reflective pixels or subpixels. In some implementations, block 1010 may involve fabricating a field lens proximate each reflective pixel or subpixel. Some implementations may involve disposing a diffuser layer between the field lenses and the reflective pixels or subpixels.

[0101] In this example, block 1015 involves disposing a layer of low-index material proximate the array of field lenses. Here, the low-index material has a refractive index that is lower than that of the field lenses. In some implementations, block 1015 may

involve disposing a layer of an optically clear resin or an optically clear adhesive on the array of field lenses.

[0102] In this implementation, block 1020 involves disposing an array of primary lenses on the layer of low-index material. In some such examples, each of the primary lenses corresponds to a distinct one of the reflective pixels and each of the primary lenses is positioned at a focal length of the primary lens. For example, block 1020 may involve disposing a film, such as a photopolymer film, that includes a plurality of field lenses. The field lenses may be diffractive optical elements.

[0103] Some implementations may involve disposing black mask material between instances of the reflective pixels. For example, disposing the black mask material may involve forming the black mask material at least partially into the layer of low-index material. In some implementations, disposing the black mask material may involve forming the black mask material from a first layer that includes the array of reflective pixels to a second layer that includes the array of primary lenses.

[0104] Figures 11A and 11B are system block diagrams illustrating a display device 40 that includes a plurality of IMOD display elements. In some implementations, the IMOD display elements may include IMODs 500 as described elsewhere herein. The display device 40 can be, for example, a smart phone, a cellular or mobile telephone. However, the same components of the display device 40 or slight variations thereof are also illustrative of various types of display devices such as televisions, computers, tablets, e-readers, hand-held devices and portable media devices.

[0105] The display device 40 includes a housing 41, a display 30, an antenna 43, a speaker 45, an input device 48 and a microphone 46. The housing 41 can be formed from any of a variety of manufacturing processes, including injection molding, and vacuum forming. In addition, the housing 41 may be made from any of a variety of materials, including, but not limited to: plastic, metal, glass, rubber and ceramic, or a combination thereof. The housing 41 can include removable portions (not shown) that may be interchanged with other removable portions of different color, or containing different logos, pictures, or symbols.

[0106] The display 30 may be any of a variety of displays, including a bi-stable or analog display, as described herein. The display 30 also can be configured to include a flat-panel display, such as plasma, EL, OLED, STN LCD, or TFT LCD, or a non-flat-panel display, such as a CRT or other tube device. In addition, the display 30 can

include an IMOD-based display. The display may include IMODs such as those described herein.

[0107] The components of the display device 40 are schematically illustrated in Figure 11A. The display device 40 includes a housing 41 and can include additional components at least partially enclosed therein. For example, the display device 40 includes a network interface 27 that includes an antenna 43 which can be coupled to a transceiver 47. The network interface 27 may be a source for image data that could be displayed on the display device 40. Accordingly, the network interface 27 is one example of an image source module, but the processor 21 and the input device 48 also may serve as an image source module. The transceiver 47 is connected to a processor 21, which is connected to conditioning hardware 52. The conditioning hardware 52 may be configured to condition a signal (such as filter or otherwise manipulate a signal). The conditioning hardware 52 can be connected to a speaker 45 and a microphone 46. The processor 21 also can be connected to an input device 48 and a driver controller 29. The driver controller 29 can be coupled to a frame buffer 28, and to an array driver 22, which in turn can be coupled to a display array 30. One or more elements in the display device 40, including elements not specifically depicted in Figure 11A, can be configured to function as a memory device and be configured to communicate with the processor 21. In some implementations, a power supply 50 can provide power to substantially all components in the particular display device 40 design.

[0108] The network interface 27 includes the antenna 43 and the transceiver 47 so that the display device 40 can communicate with one or more devices over a network. The network interface 27 also may have some processing capabilities to relieve, for example, data processing requirements of the processor 21. The antenna 43 can transmit and receive signals. In some implementations, the antenna 43 transmits and receives RF signals according to the IEEE 16.11 standard, including IEEE 16.11(a), (b), or (g), or the IEEE 802.11 standard, including IEEE 802.11a, b, g, n, and further implementations thereof. In some other implementations, the antenna 43 transmits and receives RF signals according to the Bluetooth® standard. In the case of a cellular telephone, the antenna 43 can be designed to receive code division multiple access (CDMA), frequency division multiple access (FDMA), time division multiple access (TDMA), Global System for Mobile communications (GSM), GSM/General Packet Radio Service (GPRS), Enhanced Data GSM Environment (EDGE), Terrestrial Trunked

Radio (TETRA), Wideband-CDMA (W-CDMA), Evolution Data Optimized (EV-DO), 1xEV-DO, EV-DO Rev A, EV-DO Rev B, High Speed Packet Access (HSPA), High Speed Downlink Packet Access (HSDPA), High Speed Uplink Packet Access (HSUPA), Evolved High Speed Packet Access (HSPA+), Long Term Evolution (LTE),
5 AMPS, or other known signals that are used to communicate within a wireless network, such as a system utilizing 3G, 4G or 5G technology. The transceiver 47 can pre-process the signals received from the antenna 43 so that they may be received by and further manipulated by the processor 21. The transceiver 47 also can process signals received from the processor 21 so that they may be transmitted from the display device 40 via the
10 antenna 43.

[0109] In some implementations, the transceiver 47 can be replaced by a receiver. In addition, in some implementations, the network interface 27 can be replaced by an image source, which can store or generate image data to be sent to the processor 21. The processor 21 can control the overall operation of the display device 40. The
15 processor 21 receives data, such as compressed image data from the network interface 27 or an image source, and processes the data into raw image data or into a format that can be readily processed into raw image data. The processor 21 can send the processed data to the driver controller 29 or to the frame buffer 28 for storage. Raw data typically refers to the information that identifies the image characteristics at each location within
20 an image. For example, such image characteristics can include color, saturation and gray-scale level.

[0110] The processor 21 can include a microcontroller, CPU, or logic unit to control operation of the display device 40. The conditioning hardware 52 may include amplifiers and filters for transmitting signals to the speaker 45, and for receiving signals
25 from the microphone 46. The conditioning hardware 52 may be discrete components within the display device 40, or may be incorporated within the processor 21 or other components.

[0111] The driver controller 29 can take the raw image data generated by the processor 21 either directly from the processor 21 or from the frame buffer 28 and can
30 re-format the raw image data appropriately for high speed transmission to the array driver 22. In some implementations, the driver controller 29 can re-format the raw image data into a data flow having a raster-like format, such that it has a time order suitable for scanning across the display array 30. Then the driver controller 29 sends

the formatted information to the array driver 22. Although a driver controller 29, such as an LCD controller, is often associated with the system processor 21 as a stand-alone Integrated Circuit (IC), such controllers may be implemented in many ways. For example, controllers may be embedded in the processor 21 as hardware, embedded in
5 the processor 21 as software, or fully integrated in hardware with the array driver 22.

[0112] The array driver 22 can receive the formatted information from the driver controller 29 and can re-format the video data into a parallel set of waveforms that are applied many times per second to the hundreds, and sometimes thousands (or more), of leads coming from the display's x-y matrix of display elements.

10 **[0113]** In some implementations, the driver controller 29, the array driver 22, and the display array 30 are appropriate for any of the types of displays described herein. For example, the driver controller 29 can be a conventional display controller or a bi-stable display controller (such as an IMOD display element controller). Additionally, the array driver 22 can be a conventional driver or a bi-stable display driver (such as an
15 IMOD display element driver). Moreover, the display array 30 can be a conventional display array or a bi-stable display array (such as a display including an array of IMOD display elements). In some implementations, the driver controller 29 can be integrated with the array driver 22. Such an implementation can be useful in highly integrated systems, for example, mobile phones, portable-electronic devices, watches or small-area
20 displays.

[0114] In some implementations, the input device 48 can be configured to allow, for example, a user to control the operation of the display device 40. The input device 48 can include a keypad, such as a QWERTY keyboard or a telephone keypad, a button, a switch, a rocker, a touch-sensitive screen, a touch-sensitive screen integrated with the
25 display array 30, or a pressure- or heat-sensitive membrane. The microphone 46 can be configured as an input device for the display device 40. In some implementations, voice commands through the microphone 46 can be used for controlling operations of the display device 40.

[0115] The power supply 50 can include a variety of energy storage devices. For
30 example, the power supply 50 can be a rechargeable battery, such as a nickel-cadmium battery or a lithium-ion battery. In implementations using a rechargeable battery, the rechargeable battery may be chargeable using power coming from, for example, a wall socket or a photovoltaic device or array. Alternatively, the rechargeable battery can be

wirelessly chargeable. The power supply 50 also can be a renewable energy source, a capacitor, or a solar cell, including a plastic solar cell or solar-cell paint. The power supply 50 also can be configured to receive power from a wall outlet.

[0116] In some implementations, control programmability resides in the driver controller 29 which can be located in several places in the electronic display system. In some other implementations, control programmability resides in the array driver 22. The above-described optimization may be implemented in any number of hardware and/or software components and in various configurations.

[0117] As used herein, a phrase referring to “at least one of” a list of items refers to any combination of those items, including single members. As an example, “at least one of: a, b, or c” is intended to cover: a, b, c, a-b, a-c, b-c, and a-b-c.

[0118] The various illustrative logics, logical blocks, modules, circuits and algorithm steps described in connection with the implementations disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. The interchangeability of hardware and software has been described generally, in terms of functionality, and illustrated in the various illustrative components, blocks, modules, circuits and steps described above. Whether such functionality is implemented in hardware or software depends upon the particular application and design constraints imposed on the overall system.

[0119] The hardware and data processing apparatus used to implement the various illustrative logics, logical blocks, modules and circuits described in connection with the aspects disclosed herein may be implemented or performed with a general purpose single- or multi-chip processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, or, any conventional processor, controller, microcontroller, or state machine. A processor also may be implemented as a combination of computing devices, such as a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. In some implementations, particular steps and methods may be performed by circuitry that is specific to a given function.

[0120] In one or more aspects, the functions described may be implemented in hardware, digital electronic circuitry, computer software, firmware, including the structures disclosed in this specification and their structural equivalents thereof, or in any combination thereof. Implementations of the subject matter described in this specification also can be implemented as one or more computer programs, i.e., one or more modules of computer program instructions, encoded on a computer storage media for execution by, or to control the operation of, data processing apparatus.

[0121] If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. The steps of a method or algorithm disclosed herein may be implemented in a processor-executable software module which may reside on a computer-readable medium. Computer-readable media includes both computer storage media and communication media including any medium that can be enabled to transfer a computer program from one place to another. A storage media may be any available media that may be accessed by a computer. By way of example, and not limitation, such computer-readable media may include RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that may be used to store desired program code in the form of instructions or data structures and that may be accessed by a computer. Also, any connection can be properly termed a computer-readable medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk, and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above also may be included within the scope of computer-readable media. Additionally, the operations of a method or algorithm may reside as one or any combination or set of codes and instructions on a machine readable medium and computer-readable medium, which may be incorporated into a computer program product.

[0122] Various modifications to the implementations described in this disclosure may be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of this disclosure. Thus, the claims are not intended to be limited to the implementations shown herein, but are to be accorded the widest scope consistent with this disclosure, the principles and the novel features disclosed herein. Additionally, a

person having ordinary skill in the art will readily appreciate, the terms “upper” and “lower” are sometimes used for ease of describing the figures, and indicate relative positions corresponding to the orientation of the figure on a properly oriented page, and may not reflect the proper orientation of, e.g., an IMOD display element as implemented.

[0123] Certain features that are described in this specification in the context of separate implementations also can be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation also can be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

[0124] Similarly, while operations are depicted in the drawings in a particular order, a person having ordinary skill in the art will readily recognize that such operations need not be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Further, the drawings may schematically depict one more example processes in the form of a flow diagram.

However, other operations that are not depicted can be incorporated in the example processes that are schematically illustrated. For example, one or more additional operations can be performed before, after, simultaneously, or between any of the illustrated operations. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products. Additionally, other implementations are within the scope of the following claims. In some cases, the actions recited in the claims can be performed in a different order and still achieve desirable results.

CLAIMS

What is claimed is:

1. A reflective display, comprising:
an array of reflective pixels;
5 an array of primary lenses, each of the primary lenses corresponding to a distinct one of the reflective pixels; and
an array of field lenses, each of the field lenses corresponding to a distinct one of the reflective pixels and one of the primary lenses, each of the field lenses being positioned at a distance from a corresponding primary lens, the distance being a focal
10 length of the corresponding primary lens, each of the field lenses being disposed proximate a corresponding reflective pixel.
2. The reflective display of claim 1, wherein light is constrained by the primary lenses and the field lenses to be incident upon the reflective pixels within an angle range.
- 15 3. The reflective display of claim 2, wherein the angle range is defined, at least in part, by an F-number of the primary lenses.
4. The reflective display of claim 1, wherein the primary lenses and the field lenses are diffractive optical elements.
5. The reflective display of claim 1, wherein the primary lenses are disposed within
20 a photopolymer film.
6. The reflective display of claim 1, further comprising black mask material disposed between instances of the reflective pixels.
7. The reflective display of claim 6, wherein:
the reflective pixels are disposed in a first layer;
25 the primary lenses are disposed in a second layer; and
the black mask material extends from the first layer to the second layer.

8. The reflective display of claim 6, wherein:
the array of reflective pixels is disposed in a first layer;
the primary lenses are disposed in a second layer;
the field lenses are disposed in a third layer;
5 a fourth layer is disposed between the second layer and the third layer; and
the black mask material extends from the first layer at least partially into the
fourth layer.
9. The reflective display of claim 1, further comprising a layer of low-index
material disposed between the primary lenses and the field lenses, the low-index
10 material having a refractive index that is lower than that of the primary lenses and the
field lenses.
10. The reflective display of claim 1, further comprising a diffuser layer disposed
between the field lenses and the reflective pixels.
11. The reflective display of claim 1, wherein the reflective pixels include
15 interferometric modulator (IMOD) pixels or reflective liquid crystal display (LCD)
pixels.
12. A display device that includes the reflective display of claim 1.
13. The display device of claim 12, further including a control system capable of
controlling the display device and is capable of processing image data, wherein the
20 control system further comprises:
a driver circuit capable of sending at least one signal to a display of the display
device; and
a controller capable of sending at least a portion of the image data to the driver
circuit.
- 25 14. The display device of claim 13, wherein the control system further comprises:
a processor; and
an image source module capable of sending the image data to the processor,
wherein the image source module includes one or more elements selected from a list of
elements consisting of a receiver, a transceiver, and a transmitter.

15. The display device of claim 12, further comprising:
an input device capable of receiving input data and of communicating the input data to the control system.
16. An apparatus, comprising:
5 means for reflecting incident light and modulating reflected light, the reflecting and modulating means disposed in a first layer;
means for focusing incident light into a second layer proximate the first layer, the focusing means being disposed in a third layer; and
an array of field lenses disposed in the second layer, each of the field lenses
10 corresponding to instances of the reflecting and modulating means and corresponding to instances of the focusing means, each of the field lenses being disposed proximate a corresponding instance of the reflecting and modulating means.
17. The apparatus of claim 16, wherein the incident light is constrained by the focusing means and the array of field lenses to be incident upon the reflecting and
15 modulating means within an angle range.
18. The apparatus of claim 16, further comprising:
means for masking light, the light-masking means being disposed between instances of the reflecting and modulating means, and;
a fourth layer disposed between the second layer and the third layer, wherein the
20 light-masking means extends from the first layer at least partially into the fourth layer.
19. A method of forming a reflective display, the method comprising:
forming an array of reflective pixels on a substrate;
disposing an array of field lenses proximate the array of reflective pixels, each of the field lenses corresponding to a distinct one of the reflective pixels;
25 disposing a layer of low-index material proximate the array of field lenses, the low-index material having a refractive index that is lower than that of the field lenses;
and
disposing an array of primary lenses on the layer of low-index material, each of the primary lenses corresponding to a distinct one of the reflective pixels, each of the
30 primary lenses being positioned at a distance from a corresponding field lens, the distance being a focal length of the primary lens.

20. The method of claim 19, wherein the primary lenses and the field lenses are diffractive optical elements.
21. The method of claim 19, wherein the primary lenses are disposed within a photopolymer film.
- 5 22. The method of claim 19, further comprising disposing black mask material between instances of the reflective pixels.
23. The method of claim 22, wherein disposing the black mask material involves forming the black mask material at least partially into the layer of low-index material.
24. The method of claim 22, wherein disposing the black mask material involves
10 forming the black mask material from a first layer that includes the array of reflective pixels to a second layer that includes the array of primary lenses.
25. The method of claim 19, wherein the layer of low-index material includes at least one material from a group comprising optically clear resin and optically clear adhesive.
- 15 26. The method of claim 19, further comprising disposing a diffuser layer between the field lenses and the reflective pixels.

1/14

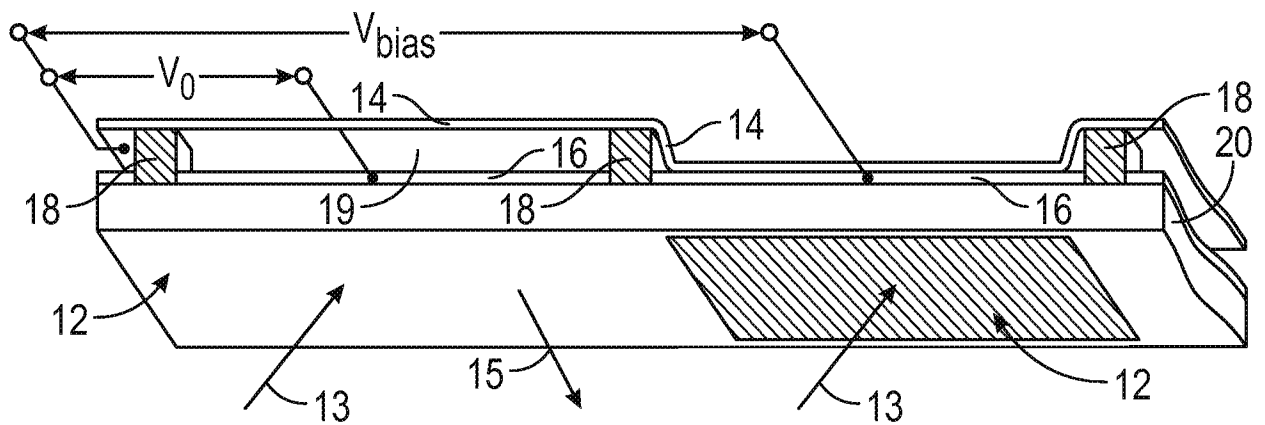


Figure 1

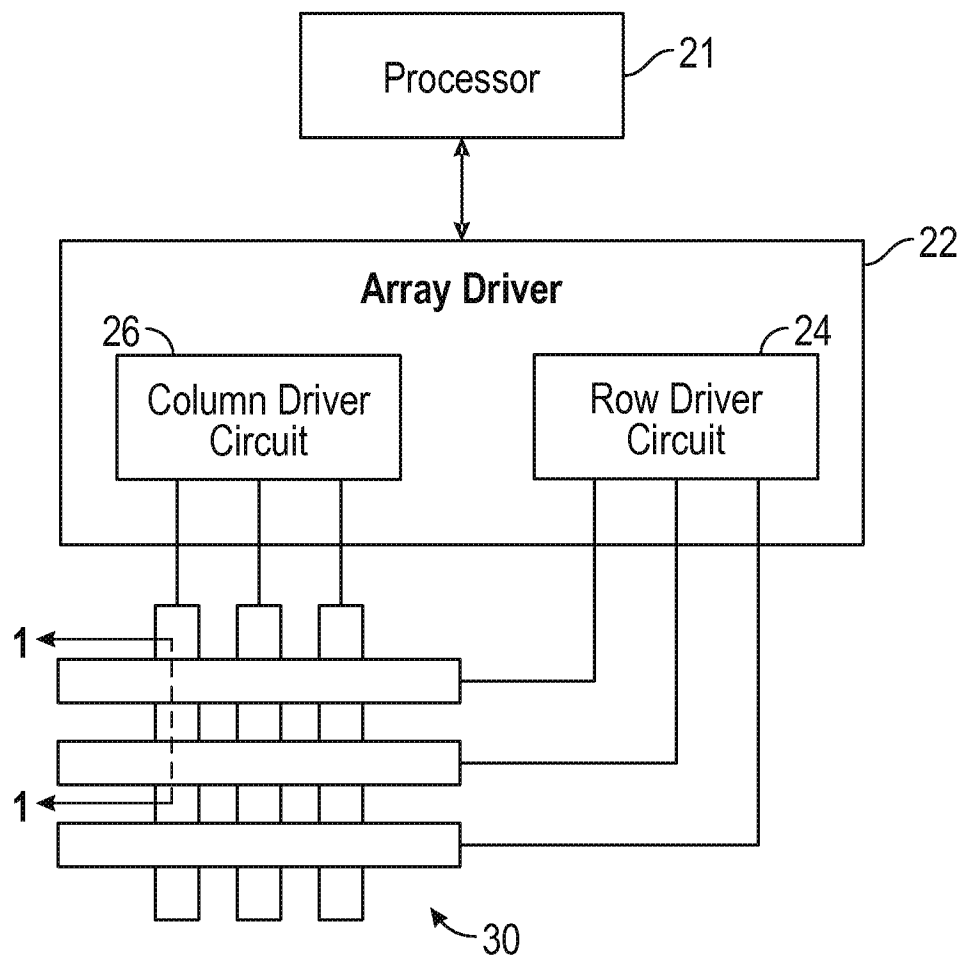


Figure 2

2/14

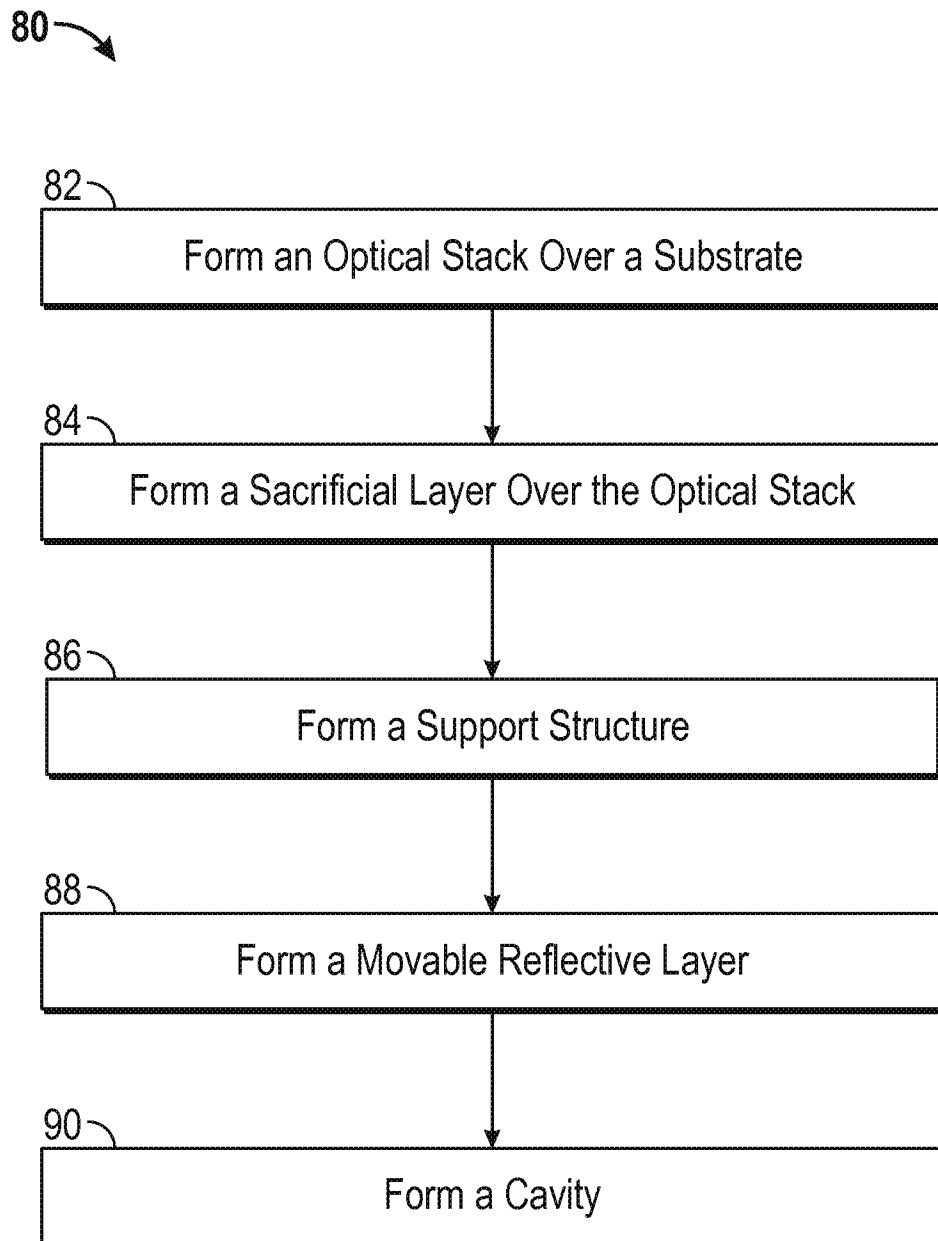


Figure 3

3/14

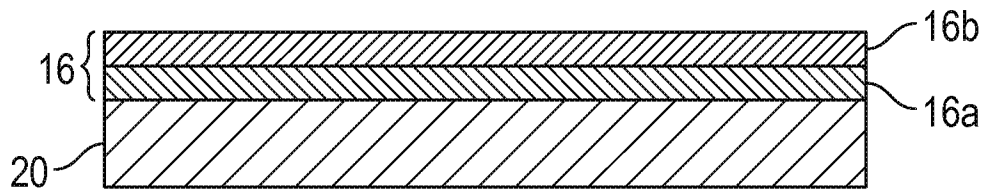


Figure 4A

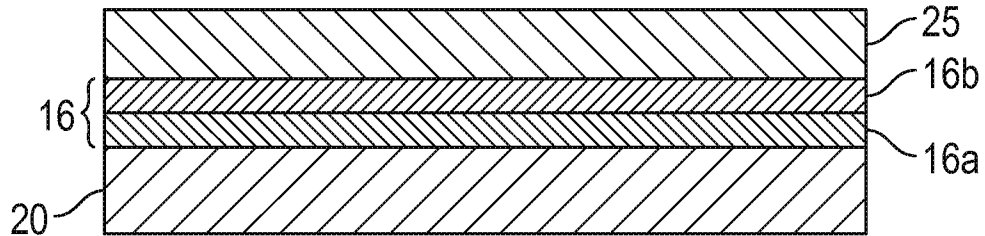


Figure 4B

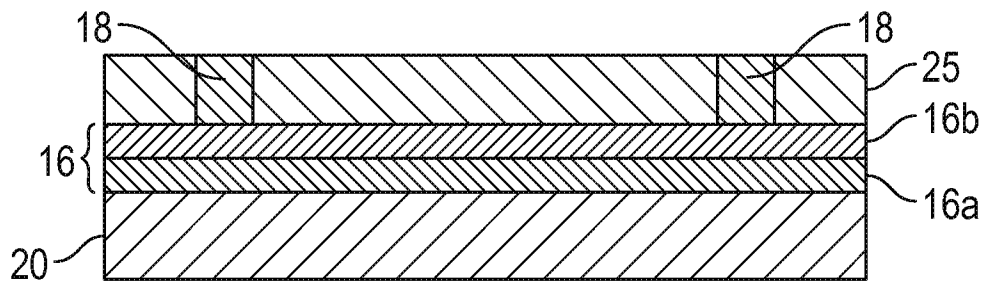


Figure 4C

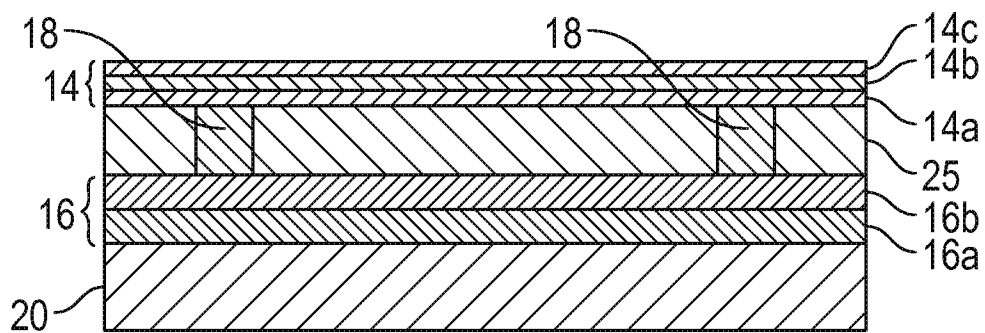


Figure 4D

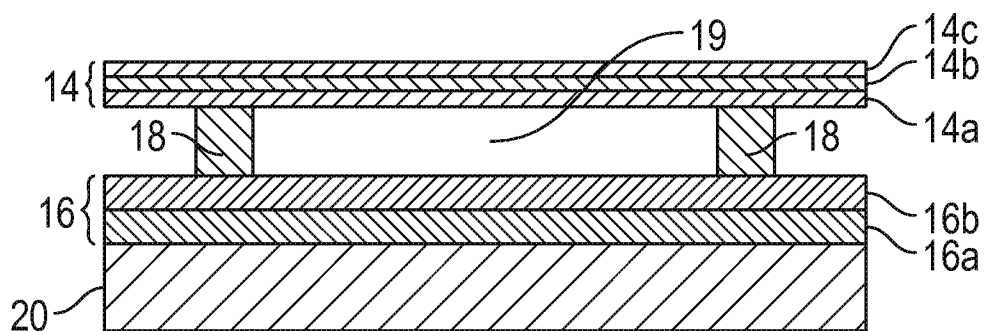
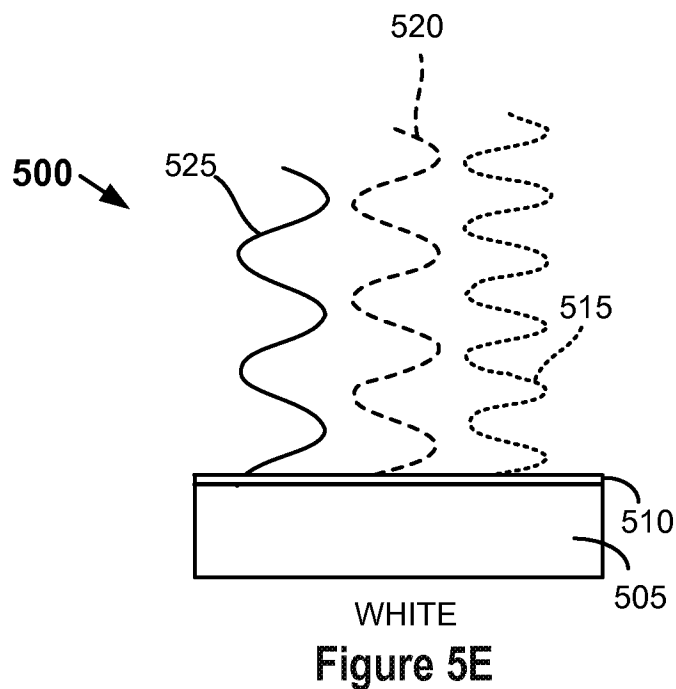
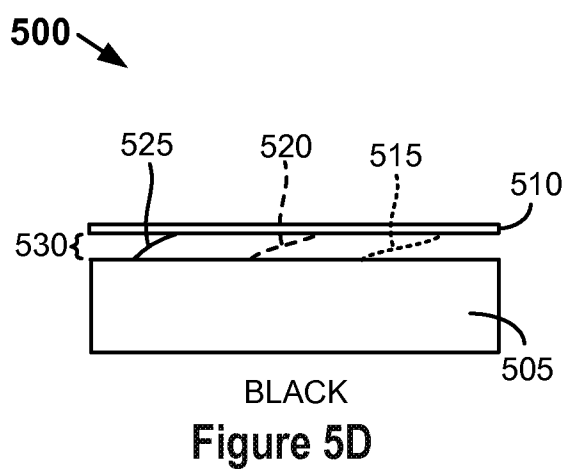
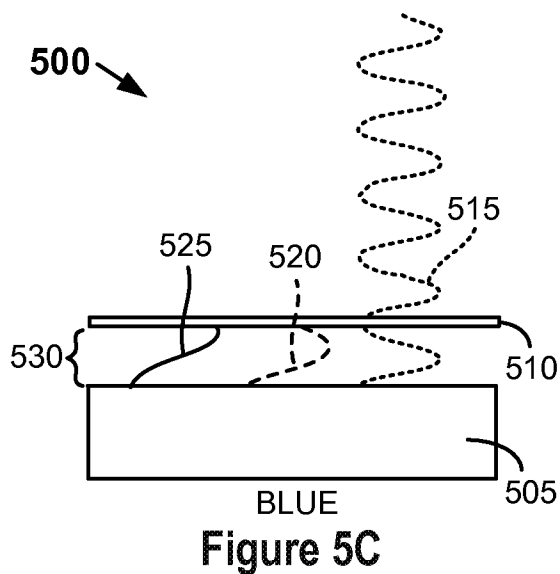
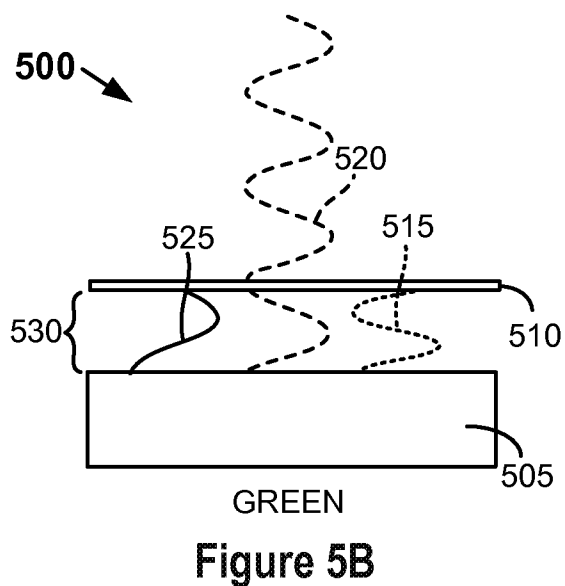
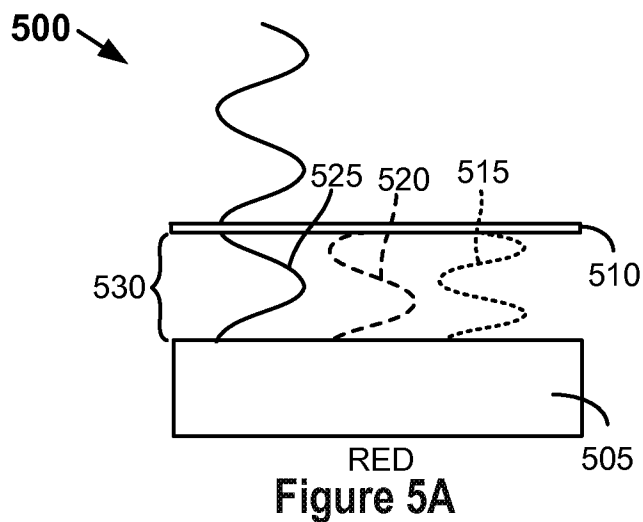


Figure 4E

4/14



5/14

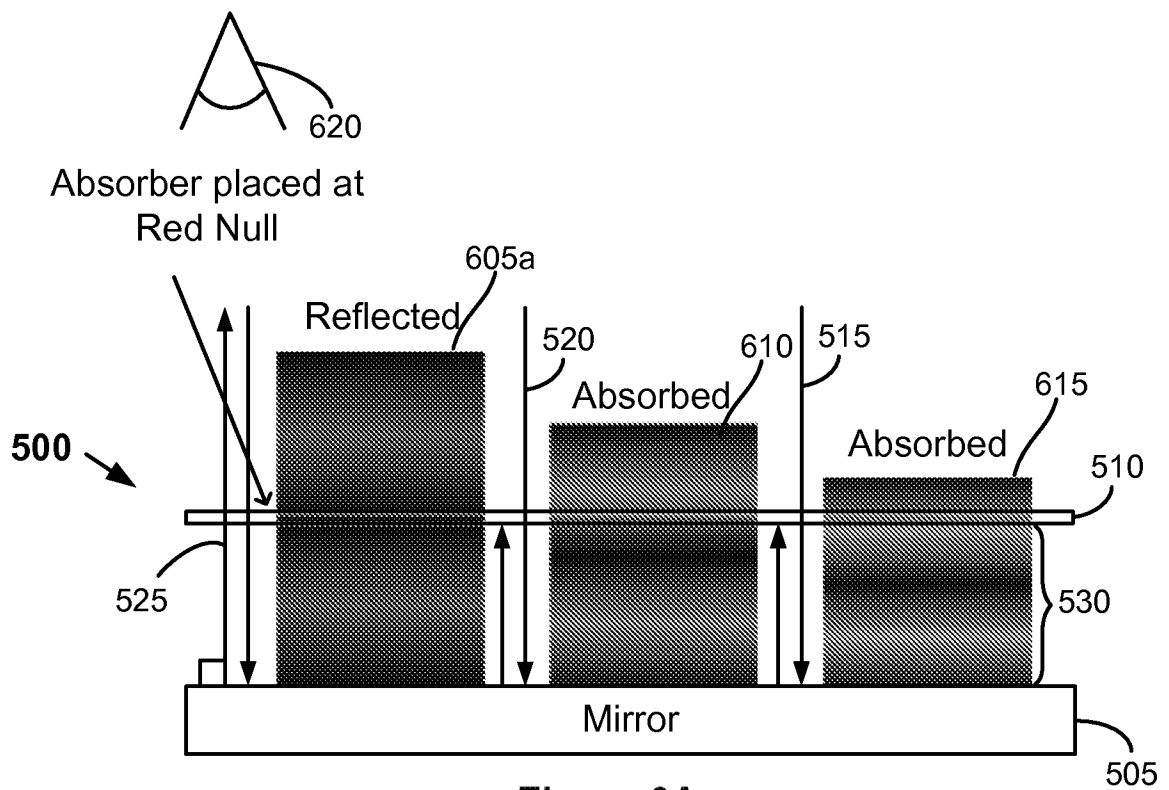


Figure 6A

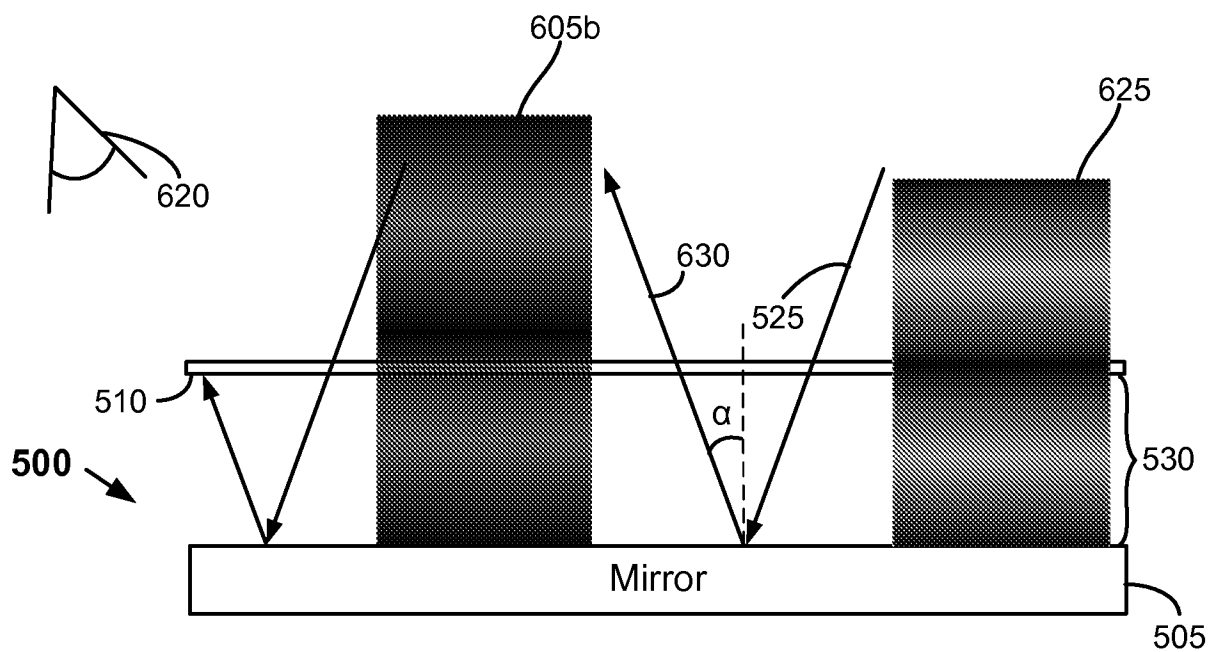


Figure 6B

6/14

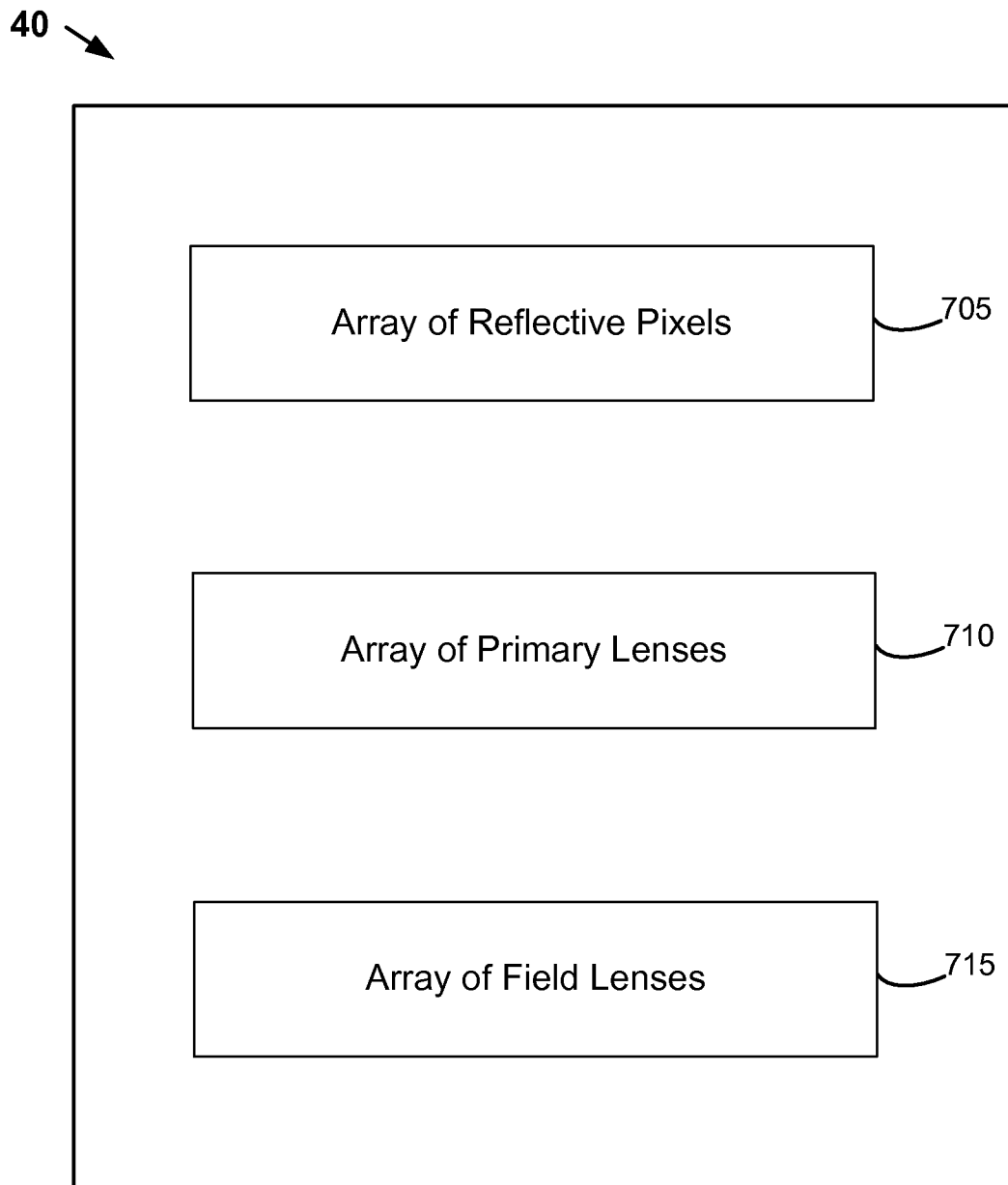


Figure 7

7/14

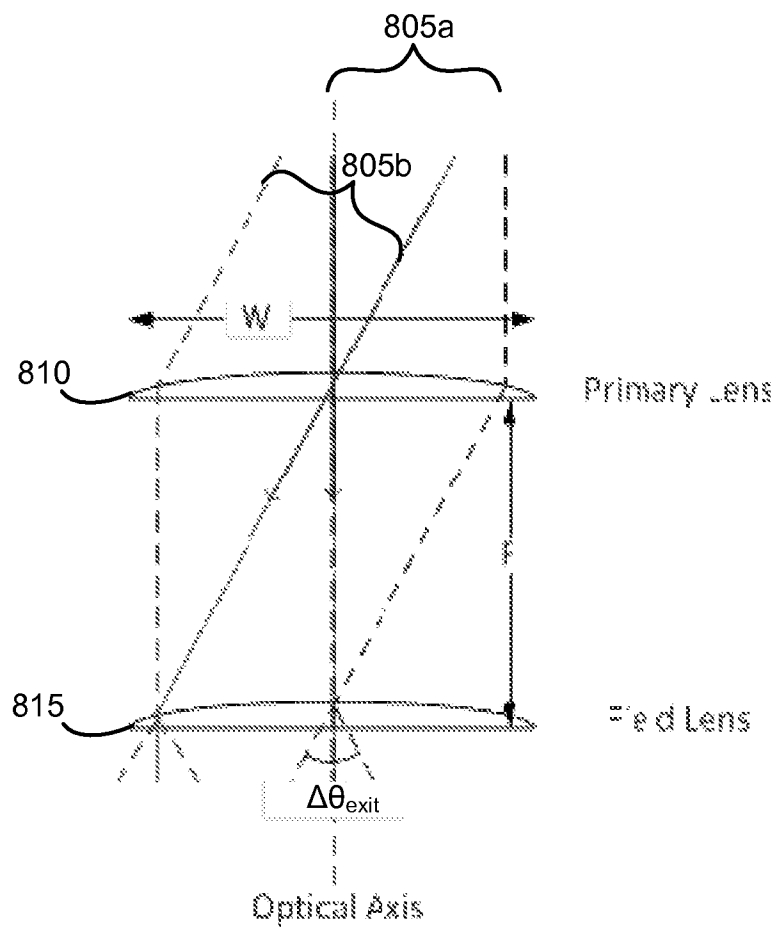


Figure 8A

8/14

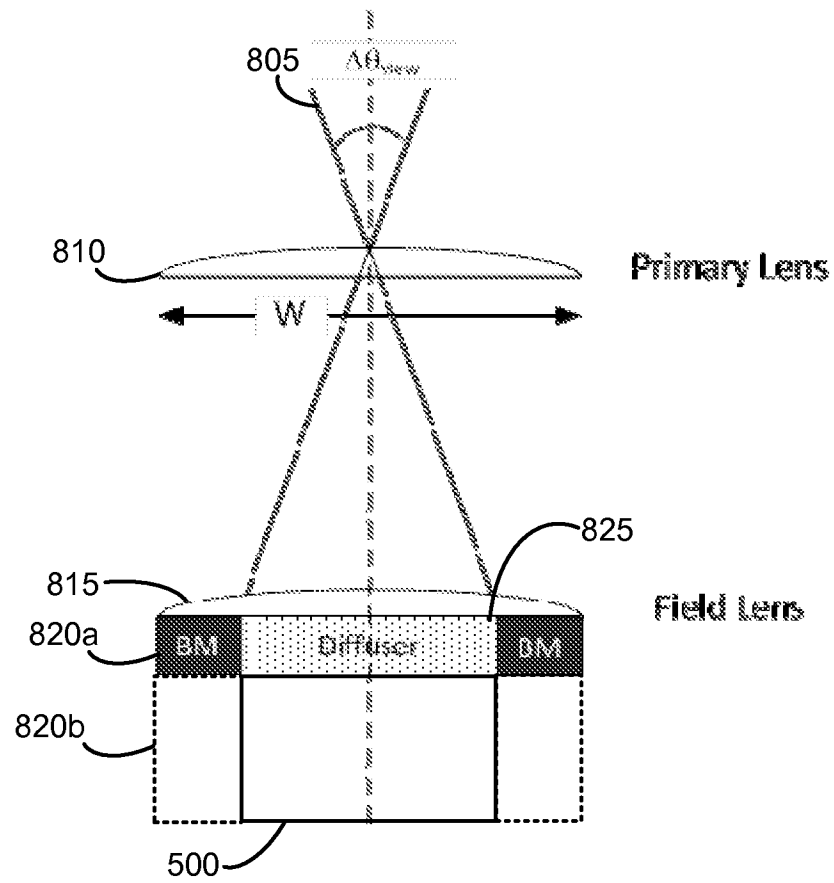


Figure 8B

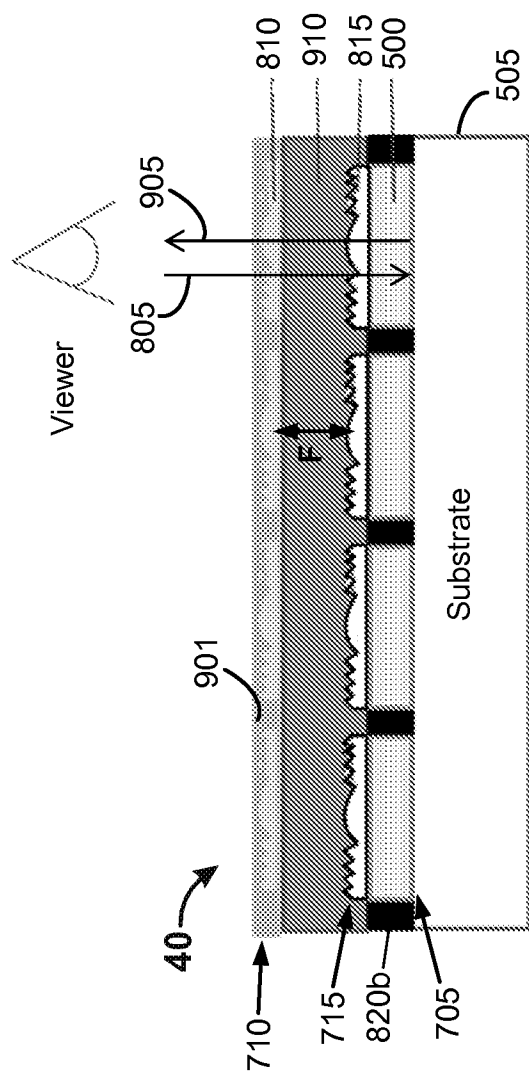


Figure 9A

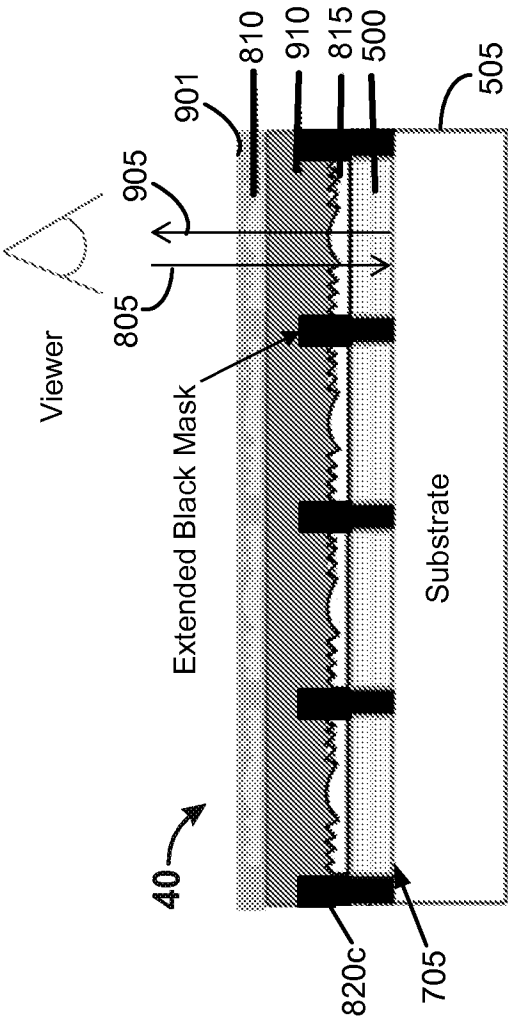


Figure 9B

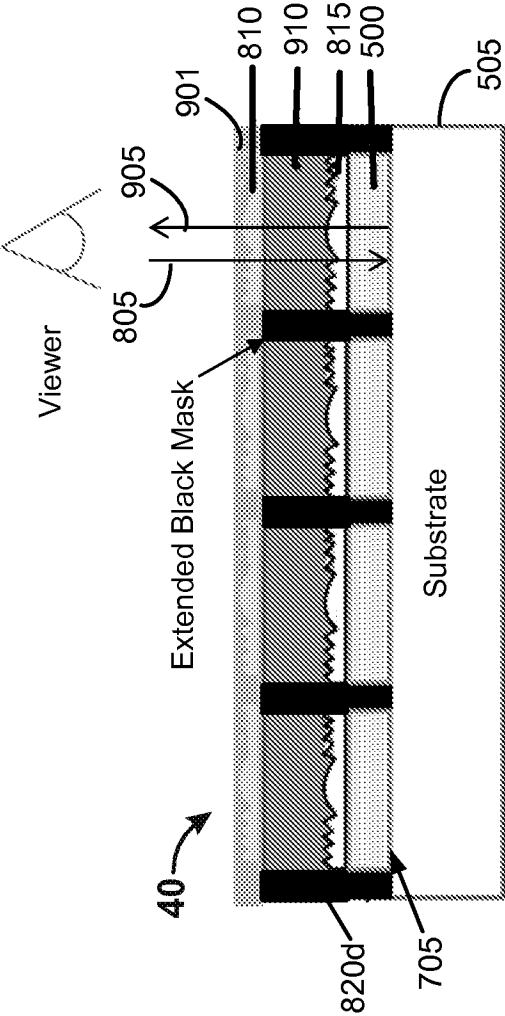


Figure 9C

12/14

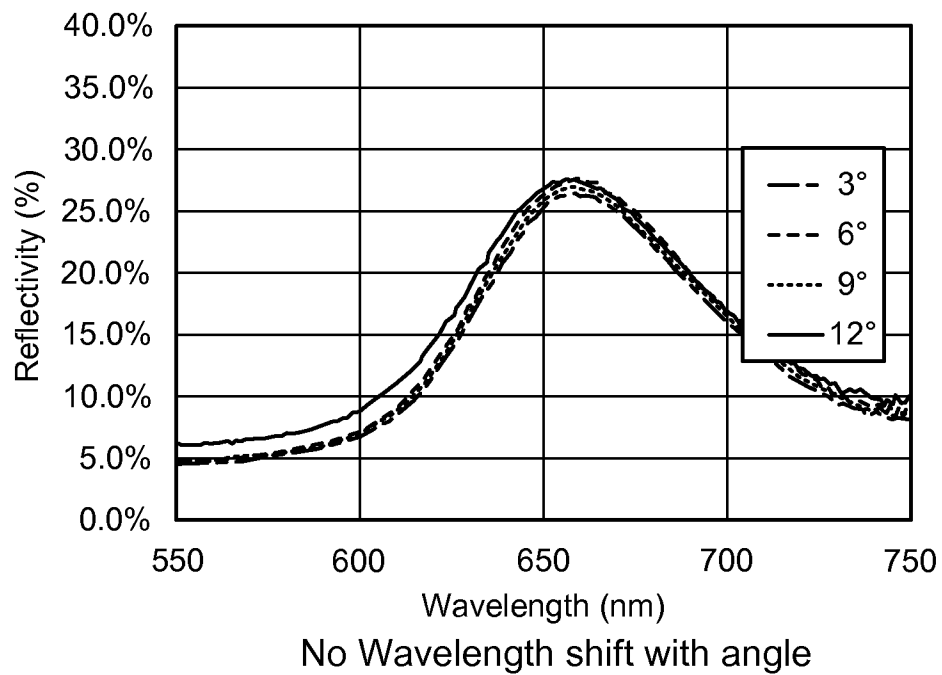


Figure 9D

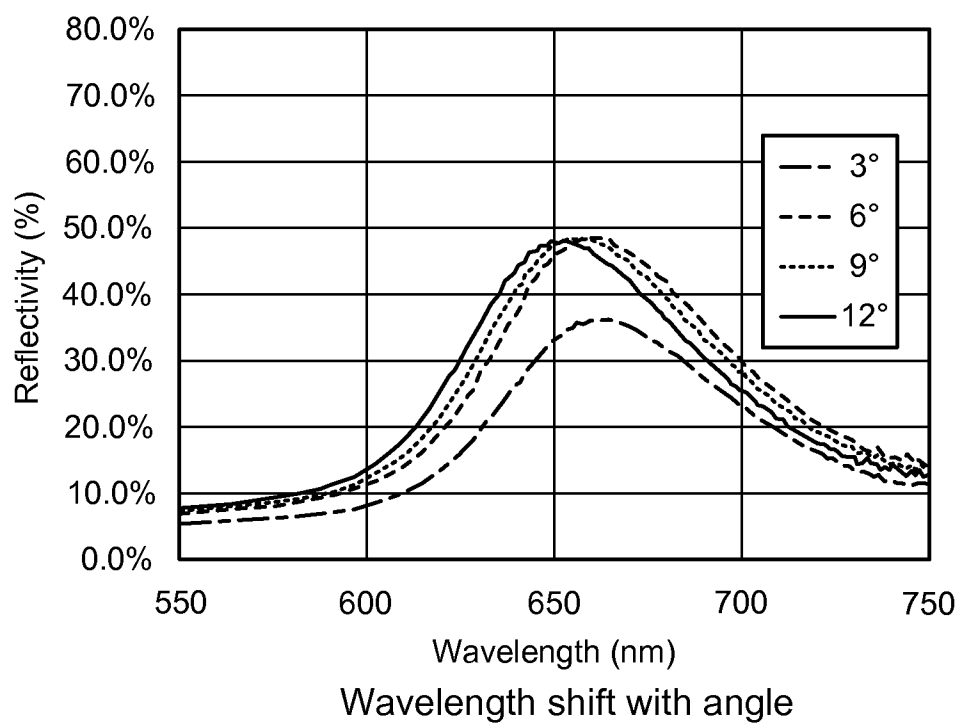


Figure 9E

13/14

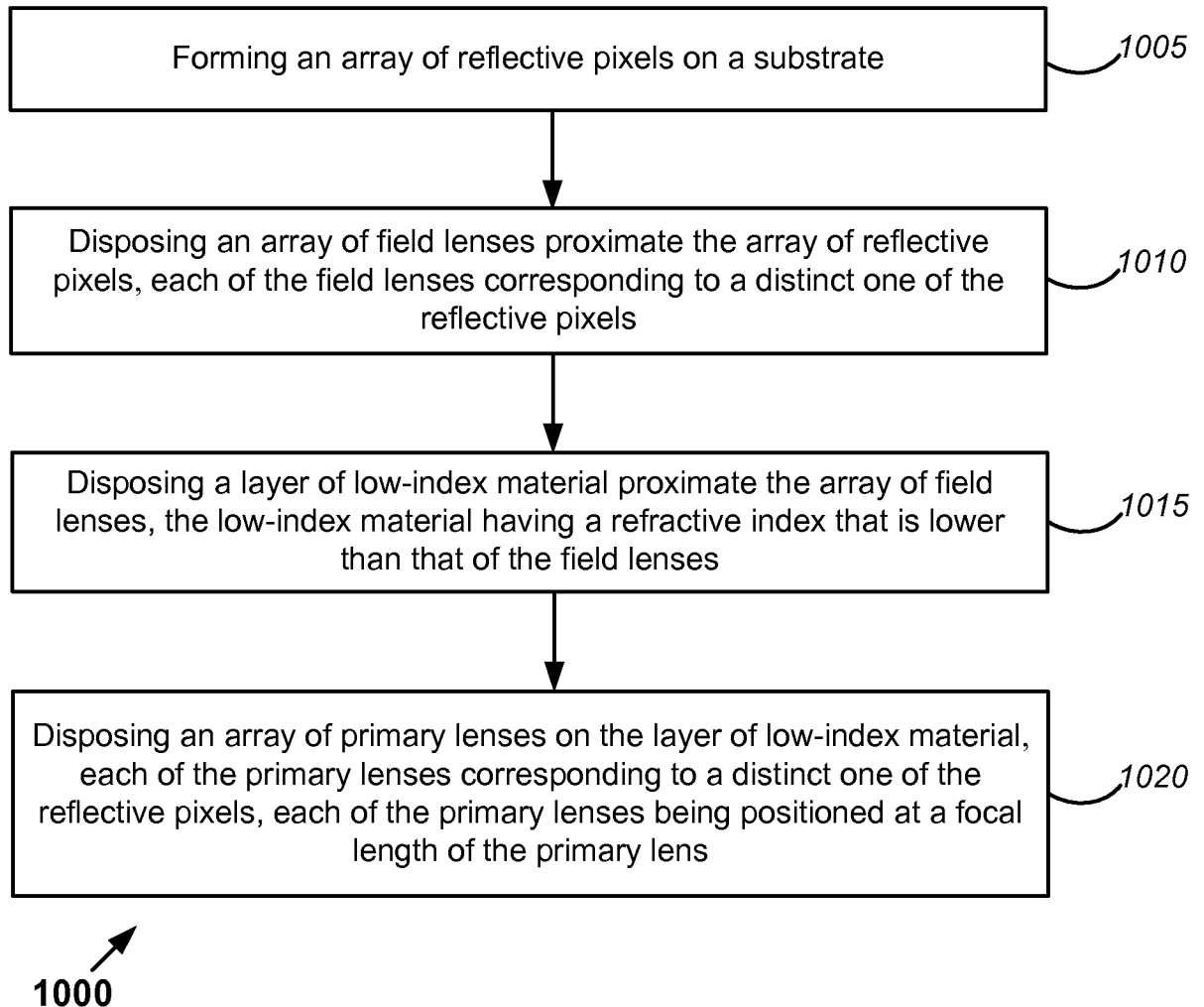


Figure 10

14/14

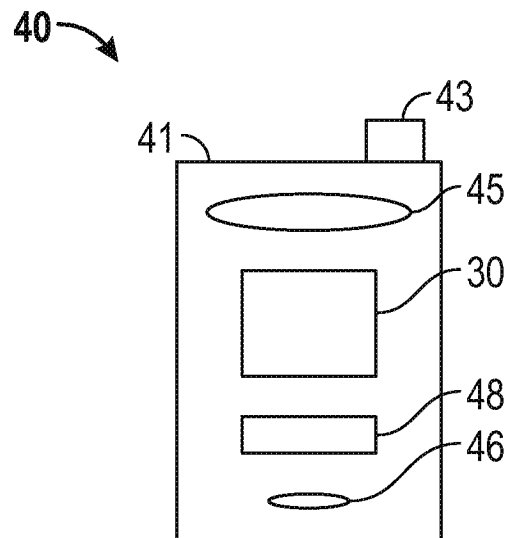


Figure 11A

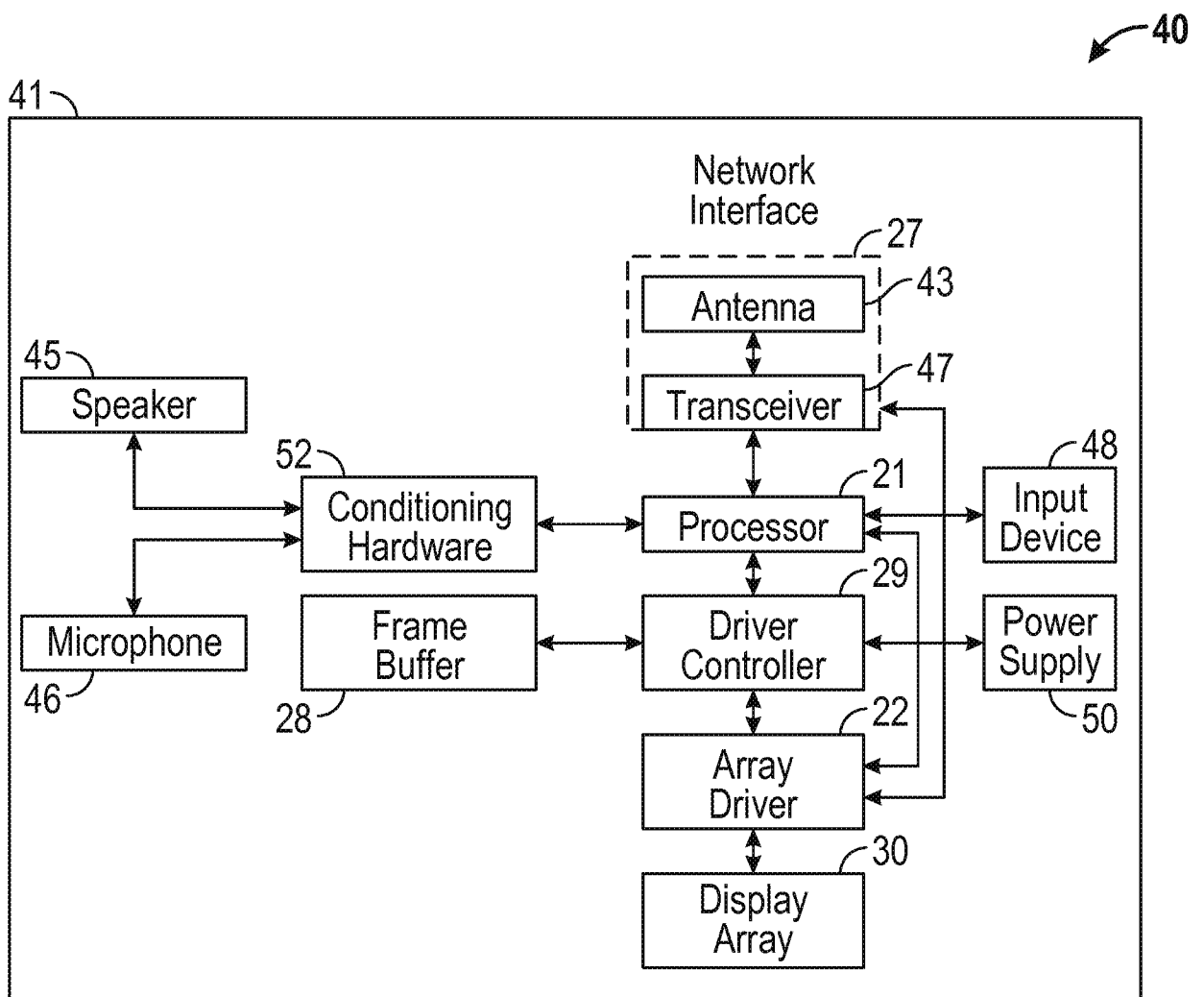


Figure 11B

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/034154

A. CLASSIFICATION OF SUBJECT MATTER

INV. G02B26/00 G02B3/00 G02F1/1335 H04N9/31
ADD.

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)

G02B G02F H04N

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)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/177253 A1 (GOLUB MICHAEL [IL]) 15 July 2010 (2010-07-15)	1-18
A	paragraph [0053] - paragraph [0056]; figures 5A-B	19

X	US 5 990 992 A (HAMANAKA KENJIRO [JP] ET AL) 23 November 1999 (1999-11-23)	1-3,9, 11-17, 19-26
	column 7, line 3 - column 8, line 37; figures 1-5 column 8, line 38 - line 50; figure 6 column 8, line 51 - column 10, line 3; figure 7	

	-/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

14 July 2015

Date of mailing of the international search report

22/07/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

A. Jacobs

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/034154

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/100700 A1 (KITAMURA KAZUYA [JP] ET AL) 27 May 2004 (2004-05-27) paragraph [0098] - paragraph [0101]; figure 3 paragraph [0123] -----	5,6,21, 22,25
A	US 2002/149717 A1 (BORRELLI NICHOLAS F [US] ET AL) 17 October 2002 (2002-10-17) paragraphs [0015], [0026], [0036]; figures 1, 3 -----	4,20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2015/034154

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010177253 A1	15-07-2010	EP 2174176 A1 JP 2010533889 A US 2010177253 A1 WO 2009010978 A1	14-04-2010 28-10-2010 15-07-2010 22-01-2009
US 5990992 A	23-11-1999	NONE	
US 2004100700 A1	27-05-2004	CN 1497268 A JP 4230187 B2 JP 2004117743 A KR 20040027372 A US 2004100700 A1	19-05-2004 25-02-2009 15-04-2004 01-04-2004 27-05-2004
US 2002149717 A1	17-10-2002	NONE	