METHOD AND DEVICE FOR COMPENSATING FOR COLOR SHIFT AS A FUNCTION OF ANGLE OF VIEW

Background

Field of the Invention

The field of the invention relates to microelectromechanical systems (MEMS).

Description of the Related Technology

Microelectromechanical systems (MEMS) include micro mechanical elements, actuators, and electronics. Micromechanical elements may be created using deposition, etching, 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. One type of MEMS device is called an interferometric modulator. An interferometric modulator may comprise a pair of conductive plates, one or both of which may be transparent and/or reflective in whole or part and capable of relative motion upon application of an appropriate electrical signal. One plate may comprise a stationary layer deposited on a substrate, the other plate may comprise a metallic membrane separated from the stationary layer by an air gap. Such devices have a wide range of applications, and it would be beneficial in the art to utilize and/or modify the characteristics of these types of devices so that their features can be exploited in improving existing products and creating new products that have not yet been developed.

Summary

The system, method, and devices of the invention each have several aspects, no single one of which is solely responsible for its desirable attributes. Without limiting the scope of this invention, its more prominent features will now be discussed briefly. After considering this discussion, and particularly after reading the section entitled "Detailed Description of Certain Embodiments" one will understand how the features of this invention provide advantages over other display devices.

One embodiment comprises a display device that includes at least one interferometric modulator configured to reflect incident light. The at least one interferometric modulator has an optical response that depends at least in part on angle of view and wavelength of the incident light. The display device further includes a diffuser positioned in an optical path to the at least one interferometric modulator. The diffuser has an optical response that is substantially matched to the optical response of the interferometric modulator to maintain substantially the composition of color at different angles of view.

Another embodiment is a method of fabricating a display device. The method includes selecting a diffuser having an optical response. The method further includes disposing the diffuser in front of an interferometric modulator array. The interferometric modulator array has an optical response that depends on angle of view. Selecting the diffuser includes substantially matching the optical response of the diffuser and the optical response of the interferometric modulator array to reduce angular color shift with angle-of-view of the display device. One embodiment is a display device manufactured according to this method.

Another embodiment comprises a display device comprising means for modulating light and means for diffusing. The modulating means is configured to reflect incident light. The modulating means has an optical response that depends at least in part on angle of view and wavelength of the incident light. The diffusing means is positioned in an optical path to the modulating means. The diffusing means has an optical response that is substantially matched to the optical response of the modulating means to maintain substantially the same composition of color at different angles of view.

Another embodiment comprises a method of displaying an image. The method comprises reflecting light from an interferometric modulator having an optical response that depends at least in part on angle of view and wavelength of the light. The method further comprises diffusing the light using a diffuser having an optical response that is substantially matched to the optical response of the intererometric modulator to maintain substantially the same composition of color at different angles of view.

Another embodiment is a display device. The display device includes at least one interferometric modulator having a spectral responsivity that varies with angle of view, θ, such that color varies with angle of view. The display device further includes a non-lambertian diffuser positioned in an optical path to the at least one interferometric modulator. The non-lambertian diffuser has an optical response that varies with angle of view. The diffuser substantially reduces variation of color with angle of view.

Another embodiment is a method of tailoring optical properties of a display device. The display device includes an interferometric modulator having a spectral responsivity and a diffuser having an optical response. The method includes selecting at least one property of the diffuser with reference to the spectral responsivity of the interferometric modulator so as to reduce color shift of the display device.

Another embodiment is a display system for producing an image. The system includes at least one interferometric modulator having a spectral responsivity that depends at least in part on angle of view of the display system. The system further includes a diffuser positioned in at least one optical path through the at least one interferometric modulator. The interferometric modulator is configured to at least partially encrypt the image from view. The diffuser is configured to decrypt the image.

One embodiment is a method of limiting view of a display to authorized viewers. The method includes selecting at least one interferometric modulator having a spectral responsivity that depends at least in part on angle of view of the display. The method further includes reflecting light indicative of an image from the at least one interferometric modulator. The interferometric modulator is configured to at least partially obscure the image from view. The method further comprises diffusing the reflected light from the at least one interferometric modulator with a diffuser having an optical response, wherein the optical response of the diffuser is configured so as to decrypt the image.

Another embodiment comprises a method of fabricating a display system for producing an image. The method comprises providing at least one interferometric modulator having a spectral responsivity that depends at least in part on angle of view of the display system. The method further comprises positioning a diffuser in at least one optical path through the at least one interferometric modulator. The interferometric modulator is configured to at least partially encrypt the image from view and the diffuser is configured to decrypt the image.

Another embodiment also comprises a display system for producing an image. The system comprising means for modulating light and a means for diffusing the light. The modulating means has a spectral responsivity that depends at least in part on angle of view of the display system. The modulating means is configured to at least partially encrypt the image from view and the diffusing means is configured to decrypt the image.

Another embodiment comprises a method of producing an image. The method comprises modulating light using a modulator having a spectral responsivity that depends at least in part on angle of view of the display and diffusing the light. The image is at least partially encrypted from view and diffusing the light decrypts the image.

In other embodiments, other types of spatial light modulators may be used, particularly those exhibiting color shift as function of viewing position.

Brief Description of the Drawings

Figure 1 is an isometric view depicting a portion of one embodiment of an interferometric modulator display in which a movable reflective layer of a first interferometric modulator is in a released position and a movable reflective layer of a second interferometric modulator is in an actuated position.

Figure 2 is a system block diagram illustrating one embodiment of an electronic device incorporating a 3x3 interferometric modulator display.

Figure 3 is a diagram of movable mirror position versus applied voltage for one exemplary embodiment of an interferometric modulator of Figure 1.

Figure 4 is an illustration of a set of row and column voltages that may be used to drive an interferometric modulator display.

Figure 5A illustrates one exemplary frame of display data in the 3x3 interferometric modulator display of Figure 2.

Figure 5B illustrates one exemplary timing diagram for row and column signals that may be used to write the frame of Figure 5A.

Figure 6A is a cross section of the device of Figure 1.

Figure 6B is a cross section of an alternative embodiment of an interferometric modulator.

Figure 6C is a cross section of another alternative embodiment of an interferometric modulator.

Figure 7 is a side cross-sectional view of an interferometric modulator display illustrating optical paths through the modulator.

Figure 8 schematically illustrates exemplary spectral responses $R(\theta_i, \lambda)$ for different angles of incidence.

Figure 9 is a side cross-sectional view of an interferometric modulator display that includes a diffuser.

Figure 10 is an exemplary graphical diagram of intensity versus view angle for various diffusers.

Figure 11 is a cross-sectional view of the interferometric modulator display of Figure 9, also showing an example of the effect of the diffuser.

Figures 12A and 12B are graphical diagrams illustrating the gain of an exemplary diffuser versus angle of view for light incident at two different angles.

Figure 13 is an exemplary graphical diagram of reflectance versus wavelength of light illustrating variation in spectral responsivity of the interferometric modulators with angle and the effects of the diffuser on the variation in spectral responsivity.

Figure 14 is a graphical diagram of color shift versus view angle illustrating an exemplary effect of the diffuser.

Figures 15A and 15B are system block diagrams illustrating an embodiment of a visual display device comprising a plurality of interferometric modulators.

Detailed Description of the Certain Embodiments

Various embodiments of the invention describe a system and method of using a diffuser with interferometric modulator devices so as to mitigate or compensate for color shift as a function of angle of view. In one embodiment of the invention, the display includes a plurality of interferometric display elements exhibiting color shift. The display further includes at least one diffuser. Optical properties of the diffuser are selected to reduce color shift of the display for at least one range of angles.

The following detailed description is directed to certain specific embodiments of the invention. However, the invention can be embodied in a multitude of different ways. In this description, reference is made to the drawings wherein like parts are designated with like numerals throughout. As will be apparent from the following description, the invention may be implemented in any device that is configured to display an image, whether in motion (e.g., video) or stationary (e.g., still image), and whether textual or pictorial. More particularly, it is contemplated that the invention may be implemented in or associated with a variety of electronic devices such as, but not limited to, mobile telephones, wireless devices, personal data assistants (PDAs), hand-held or portable computers, GPS receivers/navigators, cameras, MP3 players, camcorders, game consoles, wrist watches, clocks, calculators, television monitors, flat panel displays, computer monitors, auto displays (e.g., odometer display, etc.), cockpit controls and/or displays, display of camera views (e.g., display of a rear view camera in a vehicle), electronic photographs, electronic billboards or signs, projectors, architectural structures, packaging, and aesthetic structures (e.g., display of images on a piece of jewelry). MEMS devices of similar structure to those described herein can also be used in non-display applications such as in electronic switching devices.

One interferometric modulator display embodiment comprising an interferometric MEMS display element is illustrated in Figure 1. In these devices, the pixels are in either a bright or dark state. In the bright ("on" or "open") state, the display element reflects a large portion of incident visible light to a user. When in the dark ("off" or "closed") state, the display element reflects little incident visible light to the user. Depending on the embodiment, the light reflectance properties of the "on" and "off" states may be reversed. MEMS pixels can be configured to reflect predominantly at selected colors, allowing for a color display in addition to black and white.

Figure 1 is an isometric view depicting two adjacent pixels in a series of pixels of a visual display, wherein each pixel comprises a MEMS interferometric modulator. In some embodiments, an interferometric modulator display comprises a row/column array of these interferometric modulators. Each interferometric modulator includes a pair of reflective layers positioned at a variable and controllable distance from each other to form a resonant optical cavity with at least one variable dimension. In one embodiment, one of the reflective layers may be moved between two positions. In the first position, referred to herein as the released state, the movable layer is positioned at a relatively large distance from a fixed partially reflective layer. In the second position, the movable layer is positioned more closely adjacent to the partially reflective layer. Incident light that reflects from the two layers interferes constructively or destructively depending on the position of the movable reflective layer, producing either an overall reflective or non-reflective state for each pixel.

The depicted portion of the pixel array in Figure 1 includes two adjacent interferometric modulators 12a and 12b. In the interferometric modulator 12a on the left, a movable and highly reflective layer 14a is illustrated in a released position at a predetermined distance from a fixed partially reflective layer 16a. In the interferometric modulator 12b on the right, the movable highly reflective layer 14b is illustrated in an actuated position adjacent to the fixed partially reflective layer 16b.

The fixed layers 16a, 16b are electrically conductive, partially transparent and partially reflective, and may be fabricated, for example, by depositing one or more layers each of chromium and indium-tin-oxide onto a transparent substrate 20. The layers are patterned into parallel strips, and may form row electrodes in a display device as described further below. The movable layers 14a, 14b may be formed as a series of parallel strips of a deposited metal layer or layers (orthogonal to the row electrodes 16a, 16b) deposited on top of posts 18 and an intervening sacrificial material deposited between the posts 18. When the sacrificial material is etched away, the deformable metal layers are separated from the fixed metal layers by a defined air gap 19. A highly conductive and reflective material such as aluminum may be used for the deformable layers, and these strips may form column electrodes in a display device.

With no applied voltage, the cavity 19 remains between the layers 14a, 16a and the deformable layer is in a mechanically relaxed state as illustrated by the pixel 12a in Figure 1. However, when a potential difference is applied to a selected row and column, the capacitor formed at the intersection of the row and column electrodes at the corresponding pixel becomes charged, and electrostatic forces pull the electrodes together. If the voltage is high enough, the movable layer is deformed and is forced against the fixed layer (a dielectric material which is not illustrated in this Figure may be deposited on the fixed layer to prevent shorting and control the separation distance) as illustrated by the pixel 12b on the right in Figure 1. The behavior is the same regardless of the polarity of the applied potential difference. In this way, row/column actuation that can control the reflective vs. non-reflective pixel states is analogous in many ways to that used in conventional LCD and other display technologies.

Figures 2 through 5B illustrate one exemplary process and system for using an array of interferometric modulators in a display application. Figure 2 is a system block diagram illustrating one embodiment of an electronic device that may incorporate aspects of the invention. In the exemplary embodiment, the electronic device includes a processor 21 which may be any general purpose single- or multi-chip microprocessor such as an ARM, Pentium®, Pentium II®, Pentium III®, Pentium IV®, Pentium® Pro, an 8051, a MIPS®, a Power PC®, an ALPHA®, or any special purpose microprocessor such as a digital signal processor, microcontroller, or a programmable gate array. As is conventional in the art, the processor 21 may be configured to execute one or more software modules. In addition to executing an operating system, the

processor 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.

In one embodiment, the processor 21 is also configured to communicate with an array controller 22. In one embodiment, the array controller 22 includes a row driver circuit 24 and a column driver circuit 26 that provide signals to a pixel array 30. The cross section of the array illustrated in Figure 1 is shown by the lines 1-1 in Figure 2. For MEMS interferometric modulators, the row/column actuation protocol may take advantage of a hysteresis property of these devices illustrated in Figure 3. It may require, for example, a 10 volt potential difference to cause a movable layer to deform from the released state to the actuated state. However, when the voltage is reduced from that value, the movable layer maintains its state as the voltage drops back below 10 volts. In the exemplary embodiment of Figure 3, the movable layer does not release completely until the voltage drops below 2 volts. There is thus a range of voltage, about 3 to 7 V in the example illustrated in Figure 3, where there exists a window of applied voltage within which the device is stable in either the released or actuated state. This is referred to herein as the "hysteresis window" or "stability window." For a display array having the hysteresis characteristics of Figure 3, the row/column actuation protocol can be designed such that during row strobing, pixels in the strobed row that are to be actuated are exposed to a voltage difference of about 10 volts, and pixels that are to be released are exposed to a voltage difference of close to zero volts. After the strobe, the pixels are exposed to a steady state voltage difference of about 5 volts such that they remain in whatever state the row strobe put them in. After being written, each pixel sees a potential difference within the "stability window" of 3-7 volts in this example. This feature makes the pixel design illustrated in Figure 1 stable under the same applied voltage conditions in either an actuated or released pre-existing state. Since each pixel of the interferometric modulator, whether in the actuated or released state, is essentially a capacitor formed by the fixed and moving reflective layers, this stable state can be held at a voltage within the hysteresis window with almost no power dissipation. Essentially no current flows into the pixel if the applied potential is fixed.

In typical applications, a display frame may be created by asserting the set of column electrodes in accordance with the desired set of actuated pixels in the first row. A row pulse is then applied to the row 1 electrode, actuating the pixels corresponding to the asserted column lines. The asserted set of column electrodes is then changed to correspond to the desired set of actuated pixels in the second row. A pulse is then applied to the row 2 electrode, actuating the appropriate pixels in row 2 in accordance with the asserted column electrodes. The row 1 pixels are unaffected by the row 2 pulse, and remain in the state they were set to during the row 1 pulse. This may be repeated for the entire series of rows in a sequential fashion to produce the frame. Generally, the frames are refreshed and/or updated with new display data by continually repeating this process at some desired number of frames per second. A wide variety of protocols for driving

row and column electrodes of pixel arrays to produce display frames are also well known and may be used in conjunction with the present invention.

Figures 4, 5A, and 5B illustrate one possible actuation protocol for creating a display frame on the 3x3 array of Figure 2. Figure 4 illustrates a possible set of column and row voltage levels that may be used for pixels exhibiting the hysteresis curves of Figure 3. In the Figure 4 embodiment, actuating a pixel involves setting the appropriate column to $-V_{bias}$, and the appropriate row to $+\Delta V$, which may correspond to -5 volts and +5 volts respectively Releasing the pixel is accomplished by setting the appropriate column to $+V_{bias}$, and the appropriate row to the same $+\Delta V$, producing a zero volt potential difference across the pixel. In those rows where the row voltage is held at zero volts, the pixels are stable in whatever state they were originally in, regardless of whether the column is at $+V_{bias}$, or $-V_{bias}$.

Figure 5B is a timing diagram showing a series of row and column signals applied to the 3x3 array of Figure 2 which will result in the display arrangement illustrated in Figure 5A, where actuated pixels are non-reflective. Prior to writing the frame illustrated in Figure 5A, the pixels can be in any state, and in this example, all the rows are at 0 volts, and all the columns are at +5 volts. With these applied voltages, all pixels are stable in their existing actuated or released states.

In the Figure 5A frame, pixels (1,1), (1,2), (2,2), (3,2) and (3,3) are actuated. To accomplish this, during a "line time" for row 1, columns 1 and 2 are set to -5 volts, and column 3 is set to +5 volts. This does not change the state of any pixels, because all the pixels remain in the 3-7 volt stability window. Row 1 is then strobed with a pulse that goes from 0, up to 5 volts, and back to zero. This actuates the (1,1) and (1,2) pixels and releases the (1,3) pixel. No other pixels in the array are affected. To set row 2 as desired, column 2 is set to -5 volts, and columns 1 and 3 are set to +5 volts. The same strobe applied to row 2 will then actuate pixel (2,2) and release pixels (2,1) and (2,3). Again, no other pixels of the array are affected. Row 3 is similarly set by setting columns 2 and 3 to -5 volts, and column 1 to +5 volts. The row 3 strobe sets the row 3 pixels as shown in Figure 5A. After writing the frame, the row potentials are zero, and the column potentials can remain at either +5 or -5 volts, and the display is then stable in the arrangement of Figure 5A. It will be appreciated that the same procedure can be employed for arrays of dozens or hundreds of rows and columns. It will also be appreciated that the timing, sequence, and levels of voltages used to perform row and column actuation can be varied widely within the general principles outlined above, and the above example is exemplary only, and any actuation voltage method can be used with the present invention.

The details of the structure of interferometric modulators that operate in accordance with the principles set forth above may vary widely. For example, Figures 6A-6C illustrate three different embodiments of the moving mirror structure. Figure 6A is a cross section of the embodiment of Figure 1, where a strip of metal material 14 is deposited on orthogonally extending supports 18. In Figure 6B, the moveable reflective material 14 is attached to supports

at the corners only, on tethers 32. In Figure 6C, the moveable reflective material 14 is suspended from a deformable layer 34. This embodiment has benefits because the structural design and materials used for the reflective material 14 can be optimized with respect to the optical properties, and the structural design and materials used for the deformable layer 34 can be optimized with respect to desired mechanical properties. The production of various types of interferometric devices is described in a variety of published documents, including, for example, U.S. Published Application 2004/0051929. A wide variety of well known techniques may be used to produce the above described structures involving a series of material deposition, patterning, and etching steps.

Figure 7 is a side cross-sectional view of an interferometric modulator 12 illustrating optical paths through the modulator 12. The color of light reflected from the interferometric modulator 12 may vary for different angles of incidence (and reflection) as illustrated in Figure 7. For example, for the interferometric modulator 12 shown in Figure 7, as light travels along path A_1, the light is incident on the interferometric modulator at a first angle, reflects from the interferometric modulator, and travels to a viewer. The viewer perceives a first color when the light reaches the viewer as a result of optical interference between a pair of mirrors in the interferometric modulator 12. When the viewer moves or changes his/her location and thus view angle, the light received by the viewer travels along a different path A_2 having corresponding a second different angle of incident (and reflection). Optical interference in the interferometric modulator 12 depends on optical path length of light propagated within the modulator. Different optical path lengths for the different optical paths A_1 and A_2 therefore yield different outputs from the interferometric modulator 12. The user therefore perceives different colors depending on his or her angle of view. This phenomenon is referred to as a "color shift".

The amount of color shift may be expressed in terms of a difference in wavelength, e.g., in nanometers, for the light emitted from the interferometric modulators for different angles of incident (and reflected light). As is well known, for spectral reflection, the angle of incidence is equal to the angle of reflection. The wavelength used to measure the color shift may be the peak wavelength of the specular distribution of light output from the interferometric modulator. As used to herein, specular distribution refers to the wavelength distribution, such as for example, the intensity of light at different wavelengths.

The output of the interferometric modulator 12 may be characterized by a spectral responsivity function or spectral response $R(\theta_i, \lambda)$, where θ_i is the angle of incidence of light and λ is the wavelength. As described above, the spectral output of the interferometric modulator 12 varies with angle of incidence (and angle of reflection). Figure 8 schematically illustrates exemplary spectral responses $R(\theta_i, \lambda)$ for different angles of incidence. A first plot 110, for example, shows a spectral response (output versus wavelength) for a first angle of incidence. A

second plot 120 shows a spectral response for a second angle of incidence. The first and second plots each have peaks 115, 125, sometime referred to herein as spectral lines. These plots 110, 120 and the corresponding peaks are shifted from each other. The shift in the peaks 115, 125 for the different plots shows the color shift with angle of view.

Generally, a certain amount of perceived off-axis color shift in a display may be tolerated for certain displays. A color shift or a change, e.g., of about 5-30 nanometers in wavelength for an angle of view shift of about 40° may be acceptable for certain applications. However, in some cases, the color shift is too significant and is noticeable by the observer. In such a case, methods of correcting or compensating for such intolerable color shifts as described herein may be employed. In practice, the level of tolerance that is permissible may depend upon factors that include the intended use of the display, the quality, and/or the price range of the display. As indicated above, the level of "tolerance" in color shift may be expressed in terms of nanometers of wavelength shift for a change in view angle of a specified range. For example, in one embodiment, the tolerance may be expressed for a range between about -60° and 60°. In another embodiment, for example, a display used as part of signage, the tolerance may be expressed for a range between about -80° and 80°.

In certain preferred embodiments, a diffuser may be used to compensate for the color shift of an interferometric modulator structure. Figure 9 shows one embodiment of interferometric modulator display 200 that includes a diffuser layer 201. The interferometric modulator display 200 includes a transparent substrate 20, such as glass, having a viewing surface to which the diffuser layer 201 is attached. In one embodiment, for example, the diffuser layer 201 is formed on the top side of the substrate 20 as shown in Figure 9. Other designs are also possible.

Diffusers may comprise bulk diffuser material. For example, a diffuser may include one or more layers of a material such as a suitable transparent or translucent polymer resin, for example, polyester, polycarbonate, polyvinyl chloride (PVC), polyvinylidene chloride, polystyrene, polyacrylates, polyethylene terephthalate, polyurethane, and copolymers or blends thereof. Other materials may be employed as well. In one embodiment, the diffuser is attached to a surface of the substrate using a double-sided adhesive.

Figure 10 is a graphical diagram 300 of exemplary optical responses, referred to as $D(\theta_i, \theta)$, for a diffuser or diffuser material in accordance embodiments of the invention. Output from the diffuser may depend on both angle of incidence θ_i and on angle of transmission or angle of view, θ. Accordingly, the optical transfer function $D(\theta_i, \theta)$ may be expressed as a function of the angle of view "θ" and the angle of incidence of light "θ_i" ranging, e.g., from 0 to 90° or from 0 to -90°.

As shown in Figure 10, the vertical axis depicts the relative intensity of light from a light source that is observed through a diffuser. The horizontal axis represents the angle of viewing of

light communicated through the diffuser. The possible angle of view varies from 0 to 90 degrees on the right side of graph and from 0 to -90 degrees – left side of graph 300).

Curves or traces 310, 320, and 330 in Figure 10 depict the optical response of diffusers for a given angle of incidence, θ_i as the output varies with transmission angle or view angle θ. This angle of incidence may, for example, be 0° for the plots 310, 320, 330 in Figure 10. The plots 310, 320, 330 in Figure 10 show how much light is output from the diffuser in different directions corresponding to different angles of view, θ. For example, $D(\theta_i,0^\circ)$ corresponds to the value of $\theta = 0^\circ$ in Figure 10.

As further shown in Figure 10, the first trace 310 depicts the perceived intensity of light versus angle of viewing for a particular diffuser (and a particular angle of incidence). In one embodiment, the trace 310 has a generally a bell-shaped curve that has a relatively sharp peak at a center angle. The sharp or relatively narrow peak is located at 0° for this embodiment of the diffuser. This narrow peak may for example have a width as measured at full width half maximum of about 10-30°. This type of trace is sometimes referred to as a high gain curve.

The trace 320 depicts an optical response for a second type of diffuser. The trace 320 is a generally bell-shaped curve that has a relatively small wider peak at its center. This narrow peak may for example have a width as measured at full width half maximum of about 60-100° The trace 320, with its relatively low peak and thus somewhat flattened response profile is sometimes referred to as a low gain curve. As shown in connection with the traces 310 and 320, each optical response is shown as centered at about 0° for the purpose of illustration. As will be discussed further below, the optical response may be centered at other angles for different diffusers.

Finally, Figure 10 shows a trace 330 depicting the optical response of an ideal Lambertian diffuser. Lambertian diffusers are characterized by a substantially flat angular response profile. Thus, the trace 330 depicts an approximately straight line response having a generally fixed intensity at all angles of viewing. Conversely, non-lambertian diffusers do not have substantially flat angular response profiles. The high gain and low gain diffusers corresponding to traces 310 and 320 are examples of non-lambertian diffusers.

As discussed above, the traces 310 and 320 illustrate optical responses of various diffusers having responses that are centered around zero degrees (0°). In other embodiments, similar shaped (or other shaped) response profiles may be centered on view angles other than zero degrees, such as, for example, at ten (10), twenty (20), thirty (30), forty (40), 45 (forty five), 50 (fifty), 60 (sixty), 70 (seventy), 80 (eighty) degrees, or on any other view angle.

Accordingly, $D(\theta_i, \theta)$ may be characterized by a response profile that may be different characteristically for different angles of view. In various embodiments, for example, the diffuser 201 may be a high gain, low gain (or very low gain), or any other suitable type of diffuser therebetween, or any combination thereof. As will be apparent from the following discussion, the centering of $D(\theta_i, \theta)$ around a particular angle is relevant to computing a convolution of $D(\theta_i, \theta)$

and optical response of the interferometric modulator, without the diffuser, which is referred to as $R(\theta_i, \lambda)$.

Figure 11 is a cross-sectional view illustrating an embodiment of an interferometric modulator display 400 that includes a diffuser 402. In one embodiment, the display 400 includes an array of interferometric modulators 401. In certain embodiments, the diffuser 402 is physically coupled to a substrate 403. Light is reflected in the interferometric modulator 401 so as to pass outward through the diffuser 402. As described in further detail below, the diffuser 402 is selected based on its characteristics which influence the reflected light so as to compensate for at least a portion of the angular color shift of the interferometric modulator 401. This compensation reduces the perceived color shift as the viewing angle of a user of the modulator 401 changes. In operation, light from the light source (not shown) is incident on the modulator 401 along optical paths such as exemplary paths 410, 412, and 414. Light on the exemplary optical paths 410, 412, and 414 is incident at angles of, e.g., 20, 30, and 40 degrees. It is to be recognized that any numerical values used herein, such as the angles of incidence of light paths 410, 412, and 414, are presented for purposes of illustration and are not necessarily indicative of any embodiment.

The modulator 401 reflects the light further along the paths 410, 412, and 414. The light along the paths 410, 412, and 414 is then incident on the diffuser 402. The diffuser 402 redirects portions of the reflected light along a range of optical paths at intensities that depend upon the gain characteristics, $D(\theta_i, \theta)$, of the diffuser 402. The diffused portion of the light from optical paths 410, 412, and 414, travels to a viewing position along optical paths 416. These paths 416 are at substantially the same angle with respect to the diffuser 402 and substantially parallel for this particular exemplary viewing position 430 which is a distant viewing position.

The diffuser 402 thus operates to collect light that is incident on the modulator 401 at a range of angles and corresponding optical paths, including the paths 410, 412, and 414. This collected light is redirected. A portion of this light is redirected to the viewing position along the optical paths 416.

The diffuser 402 thus collects light from the modulator 401 (or array of modulators 401) at a range of wavelengths to produce a net optical response for the modulator 401 as modified by the diffuser 402. The net optical response is related to the convolution of the optical response $D(\theta_i, \theta)$ of the diffuser with the optical response $R(\theta_i, \lambda)$ of the modulator 401 over a range of angles of light incident on the display 400.

By controlling the characteristics, e.g., $D(\theta_i, \theta)$, of the diffuser 402 in conjunction with optical response of the modulator 401, the net optical response of the system 400 can thus be controlled to achieve a desired net optical response. In one embodiment, the characteristics of the diffuser 402 and the interferometric modulator 401 are selected so as to substantially compensate for angular color shift of the interferometric modulator 401. In another embodiment, the

characteristics of the diffuser 402 and the modulator 401 are selected so that an image formed by the modulator array alone is obscured or encrypted and is not visible. The image formed by the modulator array, however, is visible by viewing through the diffuser 402.

The overall optical characteristics of the modulator 401 together with the diffuser 402 may be modeled in terms of the convolution of the optical response (i.e., spectral reflectance or transfer function) of the modulator 401, with the optical response of the diffuser 402. An exemplary expression for this convolution is set forth below.

As noted above, the optical response $R(\theta_i, \lambda)$ of the modulator 401 is represented as a function of the angle of incidence, θ_i, and wavelength of light, λ, entering the modulator 401. As the angle of incidence is equal to the angle of reflection for specular reflection, the view angle, θ, for the modulator is equal to the angle of incidence, θ_i, on the modulator. Hence, $R(\theta_i, \lambda)$ characterizes the optical response of the modulator as a function of view angle, θ.

The intensity of the light coming out of the diffuser 402 is also generally a function of the viewing angle θ (and angle of incidence θ_i). Accordingly, as described above, the optical response of the diffuser is characterized by $D(\theta_i, \theta)$.

For the combination of the modulator 401 and the diffuser 402, the view angle, θ, of the modulator corresponds to the angle of incidence, θ_i, of the diffuser. Thus, the total or net optical response of the modulator 401 as modified by the diffuser 402 (see Fig. 11) may be expressed as $R'(\theta, \lambda)$ in accordance with the following relation:

$$R'(\theta, \lambda) = \sum_{\theta_i} D(\theta_i, \theta)\, R(\theta_i, \lambda)$$

Using the above equation, the modified spectral reflectance $R'(\theta, \lambda)$ that includes the effects of the diffuser 402 can be computed. The summation is performed for a range of angles θ_i (i.e., for θ_i = 0 to 90 degrees) in determining the responsivity $R'(\theta, \lambda)$. The result is spectral response of the display for a given view angle θ.

The spectral response of the combination of the modulator 401 and the diffuser 402 can thus be computed for a particular viewing angle and corresponding viewer position. Similarly, the spectral response for the aggregate structure comprising the modulator 401 and the diffuser 402 may be computed for multiple viewing angles and view positions to quantify color shift resulting from change in angle of view.

In one embodiment, it is desirable to define the type of overall or corrected reflectance (i.e., $R'(\theta, \lambda)$) in terms of particular criteria, e.g., acceptable or unacceptable level of color shift. For example, if the color shift at a particular angle of view (e.g., 30 degrees) is 100 nanometers, it

may be desirable to reduce such color shift to no more than 20 nanometers. In such a case, the uncompensated optical response $R(\theta_i, \lambda)$ of the modulator 401 having an undesirable 100-nanometer color shift (e.g., at 30 degrees) may be improved with a suitable diffuser so as to provide a resultant spectral response $R'(\theta, \lambda)$) having an acceptable 20-nanometer color shift. It is worth noting that these numbers are chosen arbitrarily for illustrative purpose, and any tolerance level in color shift may be used in practice. For instance in certain embodiments, the level of tolerance in color shift characteristics may depend on intended use or planned viewing conditions.

Accordingly, the desirable optical response $R'(\theta, \lambda)$ is derivable from the uncompensated optical response $R(\theta_i, \lambda)$. In this case, since the optical response of uncompensated $R(\theta_i, \lambda)$ and desired $R'(\theta, \lambda)$ are known functions, the optical response (i.e., characteristics) for $D(\theta_i, \theta)$ can be computed from the above equation. Since the above equation has only one unknown variable, $D(\theta_i, \theta)$ can be determined to define the suitable diffuser for providing the desired spectral responsivity $R'(\theta, \lambda)$. The $D(\theta_i, \theta)$, once solved may, for example, correspond to a diffuser having a high gain, a low gain, or a very low gain response, or other suitable characteristics.

In one embodiment, $D(\theta_i, \theta)$ is determined by solving permutations of the equation above (e.g., solving the deconvolution). Well known mathematical and numerical methods may be employed to perform the calculations.

As is well known in the art, diffusers may be fabricated to provide a desired optical response. Accordingly, once characteristics of $D(\theta_i, \theta)$ are determined, a suitable physical configuration and material of the diffuser 402 may then be determined to produce at least an approximation of the desired response profile $D(\theta_i, \theta)$ such that the color shift is within a desired tolerance at the target angle. In various embodiments, the physical configuration may be determined using techniques such as are known in the art. Diffusers with selected properties are available, for example, from Nitto Denko, Osaka, Japan. Additional details regarding selecting a diffuser based on the spectral response of the interferometric modulator are discussed more fully below.

To illustrate application of this optical model, calculations for determining the spectral response $R'(\theta, \lambda)$ of the combination of the modulator 401 and diffuser 402 based on the known spectral response $R(\theta_i, \lambda)$ of the modulator 401 and the known optical response $D(\theta_i, \theta)$ of the diffuser are provided.

In one embodiment, for example, the diffuser 402 is a diffuser having high gain characteristics that may be selected to reduce or compensate for the color shift. Figure 12A is a graphical diagram illustrating the gain of the exemplary diffuser 402 versus angle of view for an angle of incidence of 0°. Figure 12B is a graphical diagram illustrating the gain of the exemplary diffuser 402 versus angle of view at an angle of incidence of 10°. In this illustration, it may be assumed that the following values for $R(\theta_i, \lambda)$ are derived from the curve of the optical response (not shown):

$$R(0°, \lambda) = \begin{bmatrix} 0.5 \\ 0.9 \end{bmatrix}$$ and

$$R(10°, \lambda) = \begin{bmatrix} 0.6 \\ 0.8 \end{bmatrix}$$

In this example, the calculations are illustrated using only two angles of incidence for a single wavelength, are provided. In particular, the convolution is calculated for angle of incidence ranging from 0 to 10° with a step size of 10°. In practice, a larger range of angles may be used and the step size may be different. Likewise, it is to be understood that, values for various wavelengths may be identified at any particular angle of incidence (or angle of view); in this example, only 0° and 10° are being used.

Also, there are many different wavelengths at each angle of view; however only two values (0.5 and 0.9) for the wavelength, λ, are provided at 0 degrees (angle of incidence θ_i or angle of view) for illustration only. Similarly, two values (0.6 and 0.8) for the wavelength, λ, are provided at an angle of view of 10 degrees.

To verify that the selected diffuser 402 performs the intended color shift compensation, for example, one may compute $R'(\theta, \lambda)$ using the actual optical response $D(\theta_i, \theta)$ of the diffuser 402. To determine such compensated optical response $R'(\theta, \lambda)$ of the modulator 401 as modified by the diffuser 402, the equation above is used to compute $R'(\theta, \lambda)$ at a desired angle of view. In this example, the optical response $D(\theta_i, \theta)$ is used and it is assumed that $D(0°, 10°) = 0.5$ and $D(10°, 10°) = 0.2$ to compute the effect of the diffuser 402 at an angle of view 10°. It is to be recognized that these numbers have been selected arbitrarily to illustrate the principle described herein and are not limiting. Moreover, as discussed above, the convolution may be performed for a greater number of angles of incidence θ_i, even though in this numeric example only values at two values of θ_i are provided for $D(\theta_i, \theta)$, i.e., 0.2 and 0.5.

In performing the convolution of $D(\theta_i, \theta)$ with $R(\theta_i, \lambda)$, $R'(\theta, \lambda)$ can be computed at an angle of view of 10° (or at any desired angle of view, e.g., between 0° and 90°, in a like manner). In performing the convolution in this particular example, each value for $D(\theta_i, \theta)$ that is used is obtained from the $D(\theta_i, \theta)$ curve at the angle of view (in this example, $\theta = 10°$) for all values of θ_i.

As noted above, for each angle of view computation, the convolution is summed by varying θ_i from 0° to 90° to compute the total modified or compensated optical response $R'(\theta, \lambda)$ (as corrected by the diffuser 402). In this numeric example, the computation may operate as follows:

$$R'(10°,\lambda) = D(0°,10°) * R(0°,\lambda) + D(10°,10°) * R(10°,\lambda)$$
$$= [0.50] * \begin{bmatrix} 0.5 \\ 0.9 \end{bmatrix} + [0.20] * \begin{bmatrix} 0.6 \\ 0.8 \end{bmatrix} = \begin{bmatrix} 0.25 \\ 0.45 \end{bmatrix} + \begin{bmatrix} 0.12 \\ 0.16 \end{bmatrix} = \begin{bmatrix} 0.37 \\ 0.61 \end{bmatrix}$$

In some embodiments, the diffuser 402 may include more than one diffuser layer. In one such embodiment, the same diffuser characteristics may be selected for each of the diffuser layers. In another embodiment, different characteristics may be selected for each of the layers of the diffuser 402. In one embodiment, the diffuser characteristics of the diffuser 402 may be calculated by convolving the optical responses of each of the layers.

Figure 13 illustrates a graphical diagram 500 of several spectral reflectance traces for various configurations of interferometric modulator display devices. As shown in Figure 13, the vertical axis represents a reflectance to the viewer, expressed as a percentage (from 0 to 90%). The horizontal axis represents the wavelength of light that is reflected by the interferometric modulator. This reflectance corresponds to the spectral responsivity e.g., $R(\theta_i, \lambda)$, $R'(\theta, \lambda)$, described above.

As further shown in Figure 13, curve 510 depicts a somewhat bell-shaped curve that represents the reflectance as viewed at 0 degrees to normal from the display of one or more interferometric modulators (without the presence of a diffuser layer). The peak of curve 510 is at approximately 80% reflectance and is centered about 820 nm, which is in the infrared portion of the spectrum.

Figure 13 further depicts a curve 520 that represents the reflectance of this same display as viewed at 50 degrees to normal. The curve 520 is shaped similarly to the curve 510 but has a peak value of reflectance of approximately 84% that is located at about 690 nm.

Figure 13 also depicts a somewhat bell-shaped curve 530 that represents the reflectance as viewed at 0 degrees to normal from a display that includes a diffuser layer. The curve 530 has a

peak gain of approximately 64% that is located approximately at 750 nm. Figure 13 depicts a curve 540 that represents the reflectance of the display having the diffuser layer as viewed at 50 degrees to normal. The curve 540 follows a path that is substantially the same as the path of curve 530 with a slightly smaller peak reflectance value of 62%.

Figure 13 shows the reflectance from the modulator using input light to the interferometric modulator that is in the infrared portion of the electromagnetic spectrum at about a peak wavelength of 810 nanometers (nm). As can be seen by comparing the curves 510 and 530 to each other, the 50 degree shift in viewing angle causes an approximately 120 nm color shift in the viewed response profile. The curves 530 and 540 illustrate the spectral reflectance of the modulator when viewed through a very low gain diffuser 302 having a full width half maximum gain between 120° and 180°. Mathematically, the curves 530 and 540 represent the convolution of the response of this very low gain diffuser with that of the interferometric modulator. As shown in Figure 13, both curves 530 and 540 peak at about the same or a similar wavelength that is horizontally between the peaks of curves 510 and 520. The curves thus exhibit a very minor perceived color shift (such as in the range of about 10 to 20 nm) when the viewing angle changes by fifty degrees (50°), as in this example.

As compared to the 120 nm color shift of the modulator viewed at 50° without the diffuser layer, the diffuser layer has thus been substantially compensated for the shift in viewing angle. The peaks of the curves 530 and 540 do not shift in color substantially with changing viewing angle.

Additionally, the peaks of curves for the modulator without the diffuser that were in the infrared portion of the spectrum are in the red portion of the spectrum with the low gain diffuser. The diffuser has therefore shifted the spectral responsivity of an interferometric modulator have a peak response in the infrared to a device having a peak in a visible wavelength. Another characteristic of the effect of the diffuser is that the peak spectral reflectance of the convoluted, e.g., perceived, light signal is reduced and spread more evenly across the spectrum.

The color shift and the amount of the drop in peak reflectance may be controlled by selecting the desired wavelength and angle for the peak of the curve for a diffuser. In one embodiment, the selected diffuser may have a response that is centered about 0°. In other embodiments, the selected diffuser may have a response centered around an angle other than 0°, for example, centered at ten (10°), twenty (20), thirty (30), forty (40), 45 (forty five), 50 (fifty), 60 (sixty), 70 (seventy), 80 (eighty) degrees, or on any other view angle.

Figure 14, is a CIE 1976 chromaticity diagram 600 that illustrates a sequence of data points that show color shift versus view angle to further illustrate the effect of the embodiment of the diffuser 401 from Figure 13. The horizontal and vertical axes define a chromaticity coordinate system on which spectral tri-stimulus values may be depicted. A sequence of data points for an interferometric modulator display without diffuser is shown on the gamut color

space of the diagram along a trace 605. The curve of the trace 605 indicates that there is a considerable color shift for changes in the view angle. For the interferometric modulator display with the very low gain response, such as shown in traces 530 and 540 of Figure 13, a single data point 610 is shown on the diagram 401 because the color shift has been substantially eliminated by use of the diffuser layer

More generally, a diffuser can be selected having specific properties that produce a desired spectral responsivity, $R'(\theta,\lambda)$. Examples of properties that can be varied include the shape of the optical response $D(\theta_i, \theta)$. As discussed above, the diffuser may comprise, e.g., a non-lambertian diffuser such as a high gain, low gain, or very low gain diffuser. In the case where the optical response $D(\theta_i, \theta)$ comprises a peak, the width of this peak can be selected. For example, peaks as measured at full width half maximum may be between about 2° to 20° wide in some embodiments or between about 20° to 120° wide or larger or smaller. Peaks widths outside these ranges are also possible. In addition, the position of this peak can be controlled. Although the high and low gain response shown in Figure 10 are centered about 0°, in certain embodiments, diffusers having peaked optical response with peak at locations other than 0° may be used. Other properties of the diffuser may be varied as well.

For example, the optical responses depicted in Figure 10 are for a particular angle of incidence; however, $D(\theta_i, \theta)$ is also a function of θ_i. In various embodiments, therefore, the diffuser may be configured to provide different optical responses $D(\theta)$ for light incident at different angles of incidence θ_i. For example, the diffuser may be designed such that the width and location of peaks in the optical response are different for differing angles of incidence. The peak may for example be located at an angle of view equal (but opposite) to the angle of incidence. Alternatively, the angle of view of the peak may be different in magnitude from the angle of incidence.

Since the spectral responsivity of the interferometric modulator varies with angle, different responses for different angles of incidence may be employed to redistribute the rays to achieve the desired dependency of color on view angle. Accordingly, reduced color shift may be achieved by properly distributing the light incident on the diffuser at different angles.

Thus, by selecting the different features of the optical response $D(\theta_i, \theta)$, the desired spectral responsivity $R'(\theta,\lambda)$ may be obtained. Consideration of the spectral responsivity $R(\theta_i, \lambda)$ of the interferometric modulator may be used in determining the properties of such a suitable diffuser. Accordingly, a diffuser may be selected that appropriately matches the interferometric modulator so as, for example, to reduce color shift.

As described above, using techniques known in the art, the selection and/or design of the diffuser may be based on the known spectral and angular optical response of diffuser materials and architectures. In particular, the diffuser is selected or designed so that the convolution of the

diffuser's optical response with that of the interferometric modulator 401 produces an optical response that decreases the color shift. Thus, the color shift as viewed from at least one target angle may be reduced to within a predetermined tolerance for a particular viewing angle and particular interferometric modulator configuration 401. The predetermined tolerance may be expressed as a number of nanometers of color shift.

Holographic or diffractive optical elements may be employed as the diffuser. The diffusers may also be computer generated. In one embodiment, the desired optical response for the diffuser is produced by selecting materials, thicknesses, and arrangement of the materials of the diffuser to produce the desired optical response for the diffuser.

In certain embodiments, the interferometric modulator has a spectral response (e.g., for viewing angles at normal incidence) that is centered in the infrared or other non-visible wavelength. Such a spectral response having mostly non-visible components may contribute to reduced color shifting. For example 50%, 60%, 70% or more of the wavelengths under a central peak that extends in the visible may be non-visible. The diffuser may shift this peak into the visible.

In certain embodiments, the diffuser may exhibit a response $D(\theta_i, \theta, \lambda)$ that is a function of wavelength. In one embodiment, the diffuser includes a holographic optical element. Other types of wavelength sensitive diffusers may be employed as well.

In addition, in embodiments where a shift to the blue end of the spectrum is desired, a back light or front light may be added to provide additional intensity at desired wavelengths. The use of such frequency dependent diffuser configurations and light sources provides additional flexibility in selecting a configuration that may be viewed at a selected angle with a predetermined tolerance on color shift.

In one embodiment, the display 400 may include interferometric modulators 401 that have varying optical responses. For example, in one embodiment the display 400 includes three groups of interferometric modulators 401 having optical responses that, when the modulators 401 are matched with the diffuser 402 as disclosed herein, correspond to red, green, and blue to produce a color display. In one such embodiment, the optical response of diffuser 402 may depend on the wavelength λ of light passing through the diffuser 402. In one such embodiment, the diffuser 402 comprises a holographic optical element.

Variations in the design of the display are possible. For example, in some embodiments, a combination of several diffusers may be used to provide a display with angular color shift at a selected angle that is within a predetermined tolerance. In another embodiment, one or more diffusers may be used to provide a color shift that is within a predetermined tolerance for two, three, or a range of angles. Still other configurations are possible.

In one embodiment, an application of the interferometric modulator with diffuser is to enable encryption or obscuring of the image of a display to secure the image from unauthorized

viewing. In one embodiment, the diffuser moves data from an invisible portion of the spectrum, e.g., infrared, to a visible portion of the spectrum. The diffuser may be positioned with respect to the interferometric modulator array so that authorized viewers receive light from the display through the diffuser.

Thus, in such an embodiment, the interferometric modulator produces an encrypted image and the diffuser is configured to decrypt the image. In another embodiment, the interferometric modulator array of the display has an optical response that is selected to receive input image data and produce an output image that is difficult for the human eye to perceive, for example, in which colors are shifted such that the image is obscured. The diffuser is selected to shift the colors to a produce an image with colors indicative of the input image data.

Figures 15A and 15B are system block diagrams illustrating an embodiment of a display device 2040. The display device 2040 can be, for example, a cellular or mobile telephone. However, the same components of display device 2040 or slight variations thereof are also illustrative of various types of display devices such as televisions and portable media players.

The display device 2040 includes a housing 2041, a display 2030, an antenna 2043, a speaker 2045, an input device 2048, and a microphone 2046. The housing 2041 is generally formed from any of a variety of manufacturing processes as are well known to those of skill in the art, including injection molding, and vacuum forming. In addition, the housing 2041 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. In one embodiment the housing 2041 includes removable portions (not shown) that may be interchanged with other removable portions of different color, or containing different logos, pictures, or symbols.

The display 2030 of exemplary display device 2040 may be any of a variety of displays, including a bi-stable display, as described herein. In other embodiments, the display 2030 includes a flat-panel display, such as plasma, EL, OLED, STN LCD, or TFT LCD as described above, or a non-flat-panel display, such as a CRT or other tube device, as is well known to those of skill in the art. However, for purposes of describing the present embodiment, the display 2030 includes an interferometric modulator display, as described herein.

The components of one embodiment of exemplary display device 2040 are schematically illustrated in Figure 15B. The illustrated exemplary display device 2040 includes a housing 2041 and can include additional components at least partially enclosed therein. For example, in one embodiment, the exemplary display device 2040 includes a network interface 2027 that includes an antenna 2043 which is coupled to a transceiver 2047. The transceiver 2047 is connected to the processor 2021, which is connected to conditioning hardware 2052. The conditioning hardware 2052 may be configured to condition a signal (e.g. filter a signal). The conditioning hardware 2052 is connected to a speaker 2045 and a microphone 2046. The processor 2021 is also connected to an input device 2048 and a driver controller 2029. The driver controller 2029 is

coupled to a frame buffer 2028 and to the array driver 2022, which in turn is coupled to a display array 2030. A power supply 2050 provides power to all components as required by the particular exemplary display device 2040 design.

The network interface 2027 includes the antenna 2043 and the transceiver 2047 so that the exemplary display device 2040 can communicate with one or more devices over a network. In one embodiment the network interface 2027 may also have some processing capabilities to relieve requirements of the processor 2021. The antenna 2043 is any antenna known to those of skill in the art for transmitting and receiving signals. In one embodiment, the antenna transmits and receives RF signals according to the IEEE 802.11 standard, including IEEE 802.11(a), (b), or (g). In another embodiment, the antenna transmits and receives RF signals according to the BLUETOOTH standard. In the case of a cellular telephone, the antenna is designed to receive CDMA, GSM, AMPS or other known signals that are used to communicate within a wireless cell phone network. The transceiver 2047 pre-processes the signals received from the antenna 2043 so that they may be received by and further manipulated by the processor 2021. The transceiver 2047 also processes signals received from the processor 2021 so that they may be transmitted from the exemplary display device 2040 via the antenna 2043.

In an alternative embodiment, the transceiver 2047 can be replaced by a receiver. In yet another alternative embodiment, network interface 2027 can be replaced by an image source, which can store or generate image data to be sent to the processor 2021. For example, the image source can be a digital video disc (DVD) or a hard-disc drive that contains image data, or a software module that generates image data.

Processor 2021 generally controls the overall operation of the exemplary display device 2040. The processor 2021 receives data, such as compressed image data from the network interface 2027 or an image source, and processes the data into raw image data or into a format that is readily processed into raw image data. The processor 2021 then sends the processed data to the driver controller 2029 or to frame buffer 2028 for storage. Raw data typically refers to the information that identifies the image characteristics at each location within an image. For example, such image characteristics can include color, saturation, and gray-scale level.

In one embodiment, the processor 2021 includes a microcontroller, CPU, or logic unit to control operation of the exemplary display device 2040. Conditioning hardware 2052 generally includes amplifiers and filters for transmitting signals to the speaker 2045, and for receiving signals from the microphone 2046. Conditioning hardware 2052 may be discrete components within the exemplary display device 2040, or may be incorporated within the processor 2021 or other components.

The driver controller 2029 takes the raw image data generated by the processor 2021 either directly from the processor 2021 or from the frame buffer 2028 and reformats the raw image data appropriately for high speed transmission to the array driver 2022. Specifically, the

driver controller 2029 reformats 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 2030. Then the driver controller 2029 sends the formatted information to the array driver 2022. Although a driver controller 2029, such as a LCD controller, is often associated with the system processor 2021 as a stand-alone Integrated Circuit (IC), such controllers may be implemented in many ways. They may be embedded in the processor 2021 as hardware, embedded in the processor 2021 as software, or fully integrated in hardware with the array driver 2022.

Typically, the array driver 2022 receives the formatted information from the driver controller 2029 and reformats the video data into a parallel set of waveforms that are applied many times per second to the hundreds and sometimes thousands of leads coming from the display's x-y matrix of pixels.

In one embodiment, the driver controller 2029, array driver 2022, and display array 2030 are appropriate for any of the types of displays described herein. For example, in one embodiment, driver controller 2029 is a conventional display controller or a bi-stable display controller (e.g., an interferometric modulator controller). In another embodiment, array driver 2022 is a conventional driver or a bi-stable display driver (e.g., an interferometric modulator display). In one embodiment, a driver controller 2029 is integrated with the array driver 2022. Such an embodiment is common in highly integrated systems such as cellular phones, watches, and other small area displays. In yet another embodiment, display array 2030 is a typical display array or a bi-stable display array (e.g., a display including an array of interferometric modulators).

The input device 2048 allows a user to control the operation of the exemplary display device 2040. In one embodiment, input device 2048 includes a keypad, such as a QWERTY keyboard or a telephone keypad, a button, a switch, a touch-sensitive screen, a pressure- or heat-sensitive membrane. In one embodiment, the microphone 2046 is an input device for the exemplary display device 2040. When the microphone 2046 is used to input data to the device, voice commands may be provided by a user for controlling operations of the exemplary display device 2040.

Power supply 2050 can include a variety of energy storage devices as are well known in the art. For example, in one embodiment, power supply 2050 is a rechargeable battery, such as a nickel-cadmium battery or a lithium ion battery. In another embodiment, power supply 2050 is a renewable energy source, a capacitor, or a solar cell, including a plastic solar cell, and solar-cell paint. In another embodiment, power supply 2050 is configured to receive power from a wall outlet.

In some implementations control programmability resides, as described above, in a driver controller which can be located in several places in the electronic display system. In some cases control programmability resides in the array driver 2022. Those of skill in the art will recognize

that the above-described optimization may be implemented in any number of hardware and/or software components and in various configurations.

While the above detailed description has shown, described and pointed out the fundamental novel features of the invention as applied to various embodiments, it will be understood that various omissions and substitutions and changes in the form and details of the system illustrated may be made by those skilled in the art, without departing from the intent of the invention. The foregoing description details certain embodiments of the invention. It will be appreciated, however, that no matter how detailed the foregoing appears, the invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiment is to be considered in all respects only as illustrative and not restrictive.

CLAIMS

What is claimed is:

1. A display device comprising:

at least one interferometric modulator configured to reflect incident light, the at least one interferometric modulator having an optical response that depends at least in part on angle of view and wavelength of the incident light; and

a diffuser positioned in an optical path to the at least one interferometric modulator, the diffuser having an optical response that is substantially matched to the optical response of the interferometric modulator to maintain substantially the same composition of color at different angles of view.

2. The display device of Claim 1, wherein the optical response of the diffuser depends at least in part on angle of view.

3. The display device of Claim 1, wherein the diffuser comprises a non-lambertian diffuser.

4. The display device of Claim 1, wherein the optical response of the diffuser falls off with angle of view.

5. The display device of Claim 1, wherein the diffuser comprises a high gain diffuser.

6. The display device of Claim 5, wherein the high gain diffuser has a full width at half maximum of between about 10° and 30°.

7. The display device of Claim 1, wherein the diffuser comprises a low gain diffuser.

8. The display device of Claim 7, wherein the low gain diffuser has a full width at half maximum of between about 60° and 100°.

9. The display device of Claim 1, wherein the diffuser and interferometric modulator are configured to produce a combined optical response that reduces angular color shift to less than about 10 to 20 nanometers for an angle-of-view change of about 50 degrees.

10. The display device of Claim 1, further comprising:

a processor that is in electrical communication with said at least one interferometric modulator, said processor being configured to process image data; and

a memory device in electrical communication with said processor.

11. The display device of Claim 10, further comprising:

a driver circuit configured to send at least one signal to said at least one interferometric modulator.

12. The display device of Claim 11, further comprising:

a controller configured to send at least a portion of said image data to said driver circuit.

13. The display device of Claim 10, further comprising:

an image source module configured to send said image data to said processor.

14. The display device of Claim 13, wherein said image source module comprises at least one of a receiver, transceiver, and transmitter.

15. The display device of Claim 10, further comprising:

an input device configured to receive input data and to communicate said input data to said processor.

16. A method of fabricating a display device comprising:

selecting a diffuser having an optical response; and

disposing the diffuser in front of an interferometric modulator array, the interferometric modulator array having an optical response that depends on angle of view,

wherein selecting the diffuser comprises substantially matching the optical response of the diffuser and the optical response of the interferometric modulator array to reduce angular color shift with angle-of-view of the display device.

17. The method of Claim 16, wherein substantially matching the optical response of the diffuser and the optical response of the interferometric modulator array comprises determining the optical response of the diffuser that with the optical response of the interferometric modulator produces a combined optical response that reduces angular color shift with angle-of-view of the display to less than a predetermined tolerance.

18. The method of Claim 17, wherein the predetermined tolerance comprises a difference between a wavelength of a peak intensity of the combined optical response produced at any two angles of view within a predetermined range of angles of view.

19. The method of Claim 16, wherein the optical response of the at least one interferometric modulator has an intensity that depends at least in part on the angle of view and the wavelength of the incident light.

20. The method of Claim 16, wherein the optical response of the diffuser has an intensity that depends at least in part on angle of incidence of light and on angle of view.

21. The method of Claim 20, wherein the optical response of the diffuser further depends at least in part on the wavelength of light.

22. A display device fabricated by the method of Claim 16.

23. A display device comprising:

means for modulating light, said modulating means configured to reflect incident light, said modulator means having an optical response that depends at least in part on angle of view and wavelength of the incident light; and

means for diffusing light positioned in an optical path to said modulating means, said diffusing means having an optical response that is substantially matched to the

optical response of the modulating means to maintain substantially the same composition of color at different angles of view.

24. The display device of Claim 23, wherein said modulating means comprises an interferometric modulator.

25. The display device of Claim 24, wherein said modulator comprises a partially reflecting surface and a movable reflecting surface that form an optical cavity.

26. The display device of Claim 23, wherein said diffusing means comprises a diffuser.

27. The display device of Claim 26, wherein said diffuser comprises a diffractive optical element or a holographic optical element.

28. A method of displaying an image:

reflecting light from an interferometric modulator having an optical response that depends at least in part on angle of view and wavelength of the light; and

diffusing said light using a diffuser having an optical response that is substantially matched to the optical response of the intererometric modulator to maintain substantially the same composition of color at different angles of view.

29. A display device comprising:

at least one interferometric modulator having a spectral responsivity that varies with angle of view, θ, such that color varies with angle of view; and

a non-lambertian diffuser positioned in an optical path to the at least one interferometric modulator, the non-lambertian diffuser having an optical response that varies with angle of view, said diffuser substantially reducing variation of color with angle of view.

30. The display device of Claim 29, wherein the spectral responsivity of the interferometric modulator for a normal angle of view of 0° includes a spectral line that is centered about a non-visible wavelength and that extends into visible wavelengths.

31. The display device of Claim 30, wherein the spectral line is centered in the infrared.

32. The display device of Claim 30, wherein the spectral line is centered at a wavelength between about 700 to about 1000 nanometers.

33. The display device of Claim 30, wherein said interferometric modulator together with said diffuser have a spectral responsivity for said normal angle of view having a spectral line centered in the visible wavelength range.

34. The display device of Claim 29, wherein the diffuser comprises a high gain diffuser.

35. The display device of Claim 29, wherein the diffuser comprises a low gain diffuser.

36. The display device of Claim 29, wherein the optical response of the diffuser has a peak value at a non-zero angle of view for a normal angle of incidence.

37. The display device of Claim 36, wherein the optical response of the diffuser has a peak value at an angle of view greater than about 5 degrees for light incident on the diffuser at an angle of incidence, θ_i, of about 0°.

38. The display device of Claim 29, wherein the optical response of the diffuser is dependent on angle of incidence of light on the diffuser.

39. The display device of Claim 39, wherein the optical response of the diffuser is peaked at an angle of view that is unequal to the angle of incidence of the light on the diffuser.

40. The display device of Claim 39, wherein said peaked angle of view is different for different angles of incidence.

41. The display device of Claim 29, wherein the optical response of the diffuser further depends on the wavelength of light.

42. A method of tailoring optical properties of a display device comprising an interferometric modulator having a spectral responsivity and a diffuser having an optical response, the method comprising:

selecting at least one property of the diffuser with reference to the spectral responsivity of the interferometric modulator so as to reduce color shift of the display.

43. The method of Claim 42, wherein selecting at least one property of the diffuser comprises determining the optical response of the diffuser based on the spectral responsivity of the interferometric modulator and a desired spectral responsivity of the display device.

44. The method of Claim 43, wherein determining the optical response of the diffuser comprises calculating $D(\theta_i, \theta)$ by solving the equation,

$$R'(\theta_i, \lambda) = \sum_{\theta_i} D(\theta_i, \theta)\, R(\theta_i, \lambda)$$

45. The method of Claim 42, wherein selecting at least one property of the diffuser comprises selecting variation in diffuser response with angle of view to be peaked at an angle other than the angle of incidence of light incident on the diffuser.

46. The method of Claim 42, wherein selecting at least one property of the diffuser comprises selecting variation in response with angle of view to be peaked at an angle other than $\theta = 0°$.

47. The method of Claim 42, further comprising selecting at least one property of the interferometric modulator affecting the spectral responsivity.

48. The method of Claim 47, wherein selecting the at least one property of the diffuser comprises selecting the at least one property of the diffuser with reference to the spectral

responsivity of the interferometric modulator so as to reduce the color shift of the display to less than a predetermined target value.

49. The method of Claim 42, wherein selecting at least one property of the diffuser comprises selecting material properties of the diffuser.

50. The method of Claim 42, wherein the color shift is a difference in wavelength between spectral lines in a spectral responsivity for the display device when from viewed any two of a range of angles.

51. The method of Claim 50, wherein the range of angles is between about -40 degrees and 40 degrees with respect to an optical axis through the display device and the color shift is reduced to between about 5 and 30 nm for said range of angles.

52. A display system for producing an image, the system comprising:

at least one interferometric modulator having a spectral responsivity that depends at least in part on angle of view of the display system; and

a diffuser positioned in at least one optical path through the at least one interferometric modulator,

wherein the interferometric modulator is configured to at least partially encrypt the image from view and wherein the diffuser is configured to decrypt the image.

53. The system of Claim 52, wherein the diffuser has an optical response that depends at least in part on the wavelength of light.

54. The system of Claim 52, further comprising:

a processor that is in electrical communication with said at least one interferometric modulator, said processor being configured to process image data; and

a memory device in electrical communication with said processor.

55. The system of Claim 54, further comprising:

a driver circuit configured to send at least one signal to said at least one interferometric modulator.

56. The system of Claim 55, further comprising:

a controller configured to send at least a portion of said image data to said driver circuit.

57. The system of Claim 54, further comprising:

an image source module configured to send said image data to said processor.

58. The system of Claim 57, wherein said image source module comprises at least one of a receiver, transceiver, and transmitter.

59. The system of Claim 54, further comprising:

an input device configured to receive input data and to communicate said input data to said processor.

60. A display system for producing an image, the system comprising:

means for modulating light, said modulating means having a spectral responsivity that depends at least in part on angle of view of the display system; and

a means for diffusing said light,

wherein the modulating means is configured to at least partially encrypt the image from view and wherein the diffusing means is configured to decrypt the image.

61. The display system of Claim 60, wherein said modulating means comprises an interferometric modulator.

62. The display system of Claim 61, wherein said modulator comprises a partially reflecting surface and a movable reflecting surface that form an optical cavity.

63. The display system of Claim 62, wherein diffusing means comprises a diffuser.

64. The display system of Claim 63, wherein said diffuser comprises a diffractive optical element or a holographic optical element.

65. A method of limiting view of a display to authorized viewers, the method comprising:

selecting at least one interferometric modulator having a spectral responsivity that depends at least in part on angle of view of the display;

reflecting light indicative of an image from the at least one interferometric modulator, the interferometric modulator being configured to at least partially obscure the image from view; and

diffusing the reflected light from the at least one interferometric modulator with a diffuser having an optical response, wherein the optical response of the diffuser is configured so as to decrypt the image.

66. The method of Claim 65, wherein a spectral responsivity for the display is produced that is shifted more toward the visible wavelengths than the spectral responsivity of the interferometric modulators.

67. A method of fabricating a display system for producing an image, the method comprising:

providing at least one interferometric modulator having a spectral responsivity that depends at least in part on angle of view of the display system; and

positioning a diffuser in at least one optical path through the at least one interferometric modulator,

wherein the interferometric modulator is configured to at least partially encrypt the image from view and wherein the diffuser is configured to decrypt the image.

68. A display system fabricated by the method of Claim 67.

69. A method of producing an image, the method comprising:

modulating light using a modulator having a spectral responsivity that depends at least in part on angle of view of the display; and

diffusing said light,

wherein the image is at least partially encrypted from view and diffusing the light decrypts the image.