The arrays of SPIMs are manufactured from three continuous layers using laser-based fabrication methods.

Abstract:

The current disclosure is directed to labels and tags that employ two-dimensional arrays of self-parallelizing interferometric modulators ("SPIMs") to display digits, characters, and other symbols. Each SPIM functions as a discrete display element, containing a plurality of electrodes disposed on a bottom plate, a fixed top plate, and a movable plate separated by a cavity. Appropriate voltages are applied to the electrodes to vary the cavity depth of the SPIM in order for the SPIM to reflect a color of a particular wavelength or for the SPIM to appear black or white. The arrays of SPIMs are manufactured from three continuous layers using laser-based fabrication methods.
INTERFEROMETRIC-MODULATOR-BASED REFLECTIVE LABELS AND TAGS AND METHODS FOR THEIR MANUFACTURE

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Patent Application No. 14/282,207, filed on May 20, 2014, which claims the benefit of Provisional Application No. 61/843,491, filed July 8, 2013.

TECHNICAL FIELD

The present disclosure is generally related to reflective color displays, and particularly to reflective labels and tags based on interferometric modulators and methods by which they are manufactured.

BACKGROUND

A wide variety of display technologies have been developed to capture the characteristics of ink and paper, including transmissive liquid crystal displays ("LCDs"), reflective LCDs, electroluminescent displays, organic light-emitting diodes ("OLEDs"), electrophoretic displays, and many other display technologies. Reflective displays are a more recently developed type of display device that is gaining popularity in the market and that has already been widely used in electronic book readers. In contrast to conventional flat-panel LCD displays that require internal light sources, reflective displays utilize ambient light to display images. Reflective displays can provide images similar to those provided by traditional ink-on-paper printed materials. Due to the use of ambient light for image display, reflective displays consume substantially less power and provide more readable images in bright ambient light, than conventional displays. Currently available reflective displays are particularly effective in displaying black-and-white images. However, currently available reflective color displays can only display colors with low brightness and can only display a limited range within the full range of possible output colors, referred to as the "color gamut."
SUMMARY

The current disclosure is directed to labels and tags that employ two-dimensional arrays of self-parallelizing interferometric modulators ("SPIMs") to display digits, characters, and other symbols. Each SPIM functions as a discrete display element, containing a plurality of electrodes disposed on a bottom plate, a fixed top plate, and a movable plate separated by a cavity. Appropriate voltages are applied to the electrodes to vary the cavity depth of the SPIM in order for the SPIM to reflect a color of a particular wavelength or for the SPIM to appear black or white. The arrays of SPIMs are manufactured from three continuous layers using laser-based fabrication methods.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a typical digitally-encoded image.

Figure 2 illustrates one version of the RGB color model.

Figure 3 shows a different color model, referred to the "hue-saturation-lightness" ("HSL") color model.

Figure 4 shows color-matching functions for red, green, and blue.

Figure 5 shows the CIE 1931 xyz color-matching functions.

Figure 6 illustrates a CIE XYZ color model.

Figure 7 shows the CIE 1931 chromaticity diagram.

Figure 8A shows RGB sub-pixels of a pixel that reflects a white color in a reflective display.

Figure 8B shows RGB sub-pixels of a pixel that reflects a saturated red color in a reflective display.

Figure 9A shows a pixel that appears white using temporal color dithering in a reflective display.

Figure 9B shows a pixel that reflects a saturated red color using temporal color dithering in a reflective display.

Figure 10 is a side view of a Fabry-Perot Interferometer.
Figure 11A is an isometric view of a self-parallelizing interferometric modulator ("SPIM")

Figure 11B is an exploded view of a SPIM.

Figure 11C is a cross-section view of a TFT used in one implementation of a SPIM.

Figure 12A illustrates a cross-section view of a SPIM when the movable plate is not actuated.

Figure 12B illustrates a cross-section view of a SPIM when the movable plate is actuated.

Figure 13A is a diagram illustrating a 24-bit RGB representation of a pixel and a 32-bit representation of a pixel in the new color model.

Figure 13B is a diagram illustrating a color-system conversion from a 24-bit RGB representation to a 32-bit representation in the new color system using a fully saturated shade of red as an example.

Figure 14 provides an exemplary color look-up table.

Figure 15A shows an HSL color model used as an example to describe the conversion from a RGB system to the new color system.

Figure 15B provides an exemplary wavelength-hue look-up table for spectral hues.

Figure 15C provides an exemplary percentage-hue look-up table for non-spectral hues.

Figure 16 shows a flow chart for a routine that prepares a color look-up table, using the HSL model as an example.

Figure 17 shows a spatial dithering scheme that divides a pixel into 4 sub-pixels.

Figure 18 is a schematic display image frame.

Figure 19 shows a system diagram of a signal processing circuit of a reflective display panel.

Figure 20 illustrates a control-flow diagram for video/image processing using the reflective-color-display technology disclosed in the current document.
Figures 21A-F illustrate several example SPIM-based reflective-label implementations and characteristics of those implementations.

Figures 22A-B illustrate the patterning and cutting of the middle layer (2163 in Figure 21D).

Figures 23A-B illustrate operation of a SPIM within a SPIM-based reflective tag or label.

Figures 24-28B illustrate an example process for manufacturing a SPIM-based reflective tag or label.

Figures 29A-J illustrate an alternative manufacturing process for SPIM-based reflective labels and tags.

DETAILED DESCRIPTION

Overview of Digitally-Encoded Images and Color Models

Figure 1 illustrates a typical digitally encoded image. The encoded image comprises a two-dimensional array of pixels 102. In Figure 1, each small square, such as square 104, is a pixel, generally defined as the smallest-granularity portion of an image that is numerically specified in the digital encoding. Each pixel is a location, generally represented as a pair of numeric values corresponding to orthogonal x and y axes 106 and 108, respectively. Thus, for example, pixel 104 has x, y coordinates (39,0), while pixel 112 has coordinates (0,0). In the digital encoding, the pixel is represented by numeric values that specify how the region of the image corresponding to the pixel is to be rendered upon printing, display on a computer screen, or other display. Commonly, for black-and-white images, a single numeric value range of 0-255 is used to represent each pixel, with the numeric value corresponding to the grayscale level at which the pixel is to be rendered, with value "0" representing black and the value "255" representing white. For color images, any of a variety of different color-specifying sets of numeric values may be employed. In one common color model, as shown in Figure 1, each pixel is associated with three values, or coordinates (r,g,b) which specify the red, green, and blue components of the color to be displayed in the region corresponding to the pixel.
Figure 2 illustrates one version of the RGB color model. The entire spectrum of colors is represented, as discussed above with reference to Figure 1, by a three-primary-color coordinate \((r,g,b)\). The color model can be considered to correspond to points within a unit cube 202 within a three-dimensional color space defined by three orthogonal axes: (1) \(r\) 204; (2) \(g\) 206; and (3) \(b\) 208. Thus, the individual color coordinates range from 0 to 1 along each of the three color axes. The pure blue color, for example, of greatest possible intensity corresponds to the point 210 on the \(b\) axis with coordinates \((0,0,1)\). The color white corresponds to the point 512, with coordinates \((1,1,1)\) and the color black corresponds to the point 214, the origin of the coordinate system, with coordinates \((0,0,0)\).

Figure 3 shows a different color model, referred to as the "hue-saturation-lightness" ("HSL") color model. In this color model, colors are contained within a three-dimensional bi-pyramidal prism 300 with a hexagonal cross section. Hue \((h)\) is related to the dominant wavelength of a light radiation perceived by an observer. The value of the hue varies from \(0^\circ\) to \(360^\circ\) beginning with red 302 at \(0^\circ\), passing through green304 at \(120^\circ\), blue306 at \(240^\circ\), other intermediary colors, and ending with red 302 at \(360^\circ\). Saturation \((s)\), which ranges from 0 to 1, is inversely related to the amount of white and black mixed with a particular wavelength, or a hue. For example, the pure red color 302 is fully saturated, with saturation \(s = 1.0\), while the color pink has a saturation value less than 1.0 but greater than 0.0. White 308 is fully unsaturated, with \(s = 0.0\), and black 313 is also fully unsaturated, with \(s = 0.0\). Fully saturated colors fall on the perimeter of the middle hexagon that includes points 302, 304, and 306. A gray scale extends from black 310 to white 308 along the central vertical axis 312, representing fully unsaturated colors with no hue but different proportional combinations of black and white. For example, black 310 contains 100% of black and no white, white 308 contains 100% of white and no black and the origin 313 contains 50% of black and 50% of white. Lightness \((l)\), represented by the central vertical axis 312, indicates the illumination level, ranging from 0 at black 310, with \(l = 0.0\), to 1 at white 308, with \(l = 1.0\). For an arbitrary color, represented in Figure 3 by point 314, the hue is defined as angle \(\theta\) 16, between a first vector from the origin313 to point 302 and a second vector from the origin 313 to point 320 where a vertical line 322 that passes through point
314 intersects the plane 324 that includes the origin 313 and points 302, 304, and 306. The saturation is represented by the ratio of the distance of representative point 314 from the vertical axis 312, divided by the length of a horizontal line passing through point 320 from the origin 313 to the surface of the bi-pyramidal prism 300, d. The lightness is the vertical distance from representative point 314 to the vertical level of the point representing black 310. The coordinates for a particular color in the HSL color model, \( (h,s,l) \), can be obtained from the coordinates of the color in the RGB color model, \( (r,g,b) \), as follows:

\[
\begin{align*}
I &= \left( \frac{C_{\text{max}} - C_{\text{min}}}{2} \right) \\
\theta &= \begin{cases} 
60^\circ \times \left( \frac{g-b}{\Delta} \mod 6 \right), & \text{when } C_{\text{max}} = r \\
60^\circ \times \left( \frac{b-r}{\Delta} + 2 \right), & \text{when } C_{\text{max}} = g \\
60^\circ \times \left( \frac{r-g}{\Delta} + 4 \right), & \text{when } C_{\text{max}} = b 
\end{cases} \\
\varphi &= \begin{cases} 
0, & \lambda = 0 \\
\frac{\Delta}{1 - \frac{\Delta}{-1!}}, & \text{otherwise}
\end{cases}
\end{align*}
\]

where \( r, g, \) and \( b \) values are intensities of red, green, and blue primaries normalized to the range [0, 1]; \( C_{\text{max}} \) is a normalized intensity value equal to the maximum of \( r, g, \) and \( b \); \( C_{\text{min}} \) is a normalized intensity value equal to the minimum of \( r, g, \) and \( b \); and \( \Delta \) is defined as \( C_{\text{max}} - C_{\text{min}} \).

Figure 4 shows color-matching functions for red, green, and blue. The vertical axis 408 represents tristimulus values of the RGB primaries and the horizontal axis 410 represents wavelength \( \lambda \) in nanometers. The phrase "tristimulus value" refers to the relative intensity of a primary used in a combination of primaries to produce a perceived spectral color. It is known that under certain lighting conditions a particular combination of RGB can match most monochromatic colors.
that are visible to human eyes. A given color \( C \) can be represented by the trichromatic equation:

\[
C = B\overline{b} + G\overline{g} + R\overline{r}
\]

where \( \overline{r}, \overline{g}, \) and \( \overline{b} \) represent the three primaries, red, green, and blue and the three quantities \( R, G, \) and \( B \) are the magnitudes or relative intensities of each corresponding primary used to match the given color \( C \). The magnitudes or relative intensities \( R, G, \) and \( B \) are referred to as the "tristimulus values" with respect to the red, green, and blue primaries. However, colors in the wavelength range between 435.8 nm and 546.1 nm cannot be matched by additively combining RGB primaries. Instead, some red needs to be subtracted in order to cover the entire range of color perception.

Figure 5 shows the CIE-1931 xyz color-matching functions 502-506. The vertical axis 508 represents tristimulus values for CIE-1931xyz color-matching functions 502-506 and the horizontal axis 510 represents the wavelength \( \lambda \) in nanometers. The acronym "CIE" stands for "Commission Internationale de l'Eclairage". In 1931, the CIE established standards for color representation based on the physiological perception of light by human eyes. The CIE system is built upon a set of three CIE color-matching functions, \( \bar{x} \) 502, \( \bar{y} \) 504, and \( \bar{z} \) 506, collectively referred to as the "Standard Observer", related to the red, green, and blue cones in human eyes. Similar to the RGB color-matching function shown in Figure 4, \( \bar{x}, \bar{y}, \) and \( \bar{z} \) represent three primaries and the three tristimulus values \( X, Y, \) and \( Z \) are the relative intensities of each corresponding primary used to match a given color. The color-matching function \( \bar{y} \) 504 is chosen to match the luminance information about a color, which is the amount of energy emanating from a light source or incident upon the retina of an eye, photographic film, or a charge-coupled device.

Figure 6 shows a CIE XYZ color model. The CIE XYZ color model shown in Figure 6 is one of many CIE color models currently in use and is based on the \( \bar{x} \) 502, \( \bar{y} \) 504, and \( \bar{z} \) 506 color-matching functions shown in Figure 5. The \( X, Y, \) and \( Z \) axes in the CIE XYZ color model each represent one of the three tristimulus values \( X, Y, \) and \( Z \) discussed above. Unlike the RGB color model discussed above,
the CIE XYZ color model is not device dependent, but is instead designed to
 correspond to human perception of colors. The origin 602 corresponds to black. The
curved boundary 604 of the cone-shaped CIE XYZ color model represents the
tristimulus values of pure monochromatic colors. The coordinates for a particular
color in the CIE XYZ color model, \((X, Y, Z)\), can be obtained from the coordinates of
the color in the RGB color model, \((r, g, b)\), as follows:

\[
\begin{align*}
X &= 0.412453 \cdot r + 0.35758 \cdot g + 0.180423 \cdot b; \\
y &= 0.212671 \cdot r + 0.71516 \cdot g + 0.072169 \cdot Z; \\
Z &= 0.019334 \cdot r + 0.119193 \cdot g + 0.950227 \cdot b;
\end{align*}
\]

5

Figure 7 shows the CIE 1931 chromaticity diagram. The chromaticity
diagram is a two-dimensional projection of the three-dimensional CIE XYZ color
model shown in Figure 6. The chromaticity diagram 700 represents the mapping of
human color perception in terms of two CIE coordinates \((x, y)\) corresponding to the x
and y axes 702 and 704, respectively. In the CIE 1931 chromaticity diagram, x and y
parameters, also referred to as "chromaticity values", are determined as the
proportion of X and Y relative to the sum of all three tristimulus values, and can be
defined as:

\[
\begin{align*}
x &= \frac{X}{X + Y + Z} \\
y &= \frac{Y}{X + Y + Z}
\end{align*}
\]

10

where X, Y, and Z are CIE tristimulus values. The sum of X, Y, and Z is equal to 1.0.
The x and y parameters convey the chromatic content of a sample color.

When plotted in the \(x, y\) notation, as shown in Figure 7, the pure
monochromatic colors of the spectrum form a horseshoe shape that encompasses all
the hues that are perceivable to normal human eyes. The curved edge 706 of the
gamut is called the spectral locus and corresponds to spectral colors. Each point on
the curved edge represents a unique perceivable hue of a single wavelength, with the
wavelength listed in nanometers, including 540 and 560. All other non-spectral, less
saturated colors fall within the horseshoe shape. The degree of saturation of a color
represented by a point within the horseshoe-shaped region is inversely related to the
shortest distance of the point from the spectral locus. The straight line 708 on the
lower part of the horseshoe shape, also called the line of purples, represents the purple colors that cannot be produced using a spectral color with a single wavelength. The purple colors can be produced by mixing different combinations of blue and red. For a given purple color D, a blue ratio is calculated as the ratio of the distance from point B at one end of the purple line to point D divided by the distance from point B to point R at the other end of the purple line. White point E710 is located in the center of the horseshoe and represents a set of chromaticity coordinates that define white. For a given perceived color, for example, color T712, a straight line connecting color T and white point E can be extrapolated to two intersection points P and P' on the spectral locus. Point P, nearer to color T, reveals the dominant wavelength of color T, while point P' reveals the complementary wavelength. The two points P and P' define a complementary color pair. Mixing portions of two complementary colors produces white.

The color gamut of a given display panel is defined by the location of a set of primary colors in the chromaticity diagram. All the colors that can be realized by combining three RGB primaries of a particular RGB color model is bounded by a Maxwell triangle for that RGB color model, for example triangles 714 and 716 as shown in Figure 7, formed by the three red, green, and blue vertices. The colors enclosed by the spectral locus but outside the Maxwell triangle cannot be produced by adding the three primaries of the RGB color model. Triangle 714 in Figure 7 represents the colors that can be obtained by combining the primaries of a CIE RGB color model, while triangle 716 represents the colors that can be obtained by combining primaries of an sRGB color model. The sRGB color model is a standard RGB color model created cooperatively by Hewlett-Packard™ and Microsoft® and commonly used on monitors, printers, and the Internet.

CIE LUV and CIE LAB color models are two different color models derived from the CIE XYZ color model that are considered to be perceptually uniform. The acronym "LUV" stands for the three dimensions L*, u*, and v*, used to define the CIE LUV color model, while the acronym "LAB" stands for the three dimensions L*, a*, and b*, used to define the CIE LAB color model. As one example, in the CIELUV color model, the CIELUV coordinates, L*, u*, and v* can be
calculated from the tristimulus values XYZ using the following formulas (9-14), in which the subscript $n$ denotes the corresponding values for the white point.

\[
x^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16 \quad \text{(for } Y/Y_n > 0.008856\text{)}; \\
L^* = 903.3\left(\frac{Y}{Y_n}\right) \quad \text{(for } Y/Y_n < 0.008856\text{)}; \\
u' = 13Z^* - (u' - u'_n); \\
v' = nL^* - (v' - v'_n); \\
u' = \frac{AX}{X + 157 + 3Z}; \\
v' = \frac{97}{X + 157 + 3Z}. \\
\]

There are a variety of different, alternative color models, some suited to specifying colors of printed images and others more suitable for images displayed on CRT screens or LCD screens. In many cases, the components or coordinates that specify a particular color in one color model can be easily transformed to coordinates or values in another color model, as shown in the above examples by equations that transform RGB color coordinates to HSL color coordinates and by equations that transform CIE XYZ color coordinates to CIE LUV color coordinates. In other cases, such as converting from RGB colors to CIE LUV colors, the device-dependent RGB colors are first converted into a device-independent RGB color model and then, in a second step, transformed from the device-independent RGB color model to the CIE LUV color model.

**Color Generation Using RGB Primaries**

Engineers seek to create a display technology capable of providing a paper-like reading experience, not only with regards to appearance, but also with respect to cost, power consumption, and ease of manufacture. A wide variety of display technologies have been developed to capture the characteristics of ink and paper, including transmissive liquid crystal displays ("LCDs"), reflective LCDs, electroluminescent displays, organic light-emitting diodes ("LEDs"), and electrophoretic displays. A transmissive LCD consists of two transmissive substrates
between which a liquid crystal panel resides. By placing a backlight underneath one of the transmissive substrates and by applying a voltage to the liquid crystal, the light reaching the observer can be modulated to make the display pixel appear bright or dark. A display can also directly emit light, as in the case of an OLED display. In a reflective display, one of the transmissive substrates is replaced with a reflective substrate. Color ink or pigment is applied on top of the reflective substrate to modulate the ambient light reflecting off from the reflective substrate. The more ambient light, the brighter the display appears. This attribute simulates the response of traditional ink and paper, as a result of which reflective displays are also referred to as "E-ink" or "E-paper". Since reflective displays eliminate the need for a backlight, substantially less power is consumed in reflective displays than in emissive/transmissive displays.

Traditionally, colors are produced in displays by combining different proportions of primary colors using spatial color dithering, temporal color dithering, or a combination of both. In spatial dithering, the color of a pixel is generated by controlling sub-pixels. Figure 8A shows RGB sub-pixels of a pixel that reflects white in a reflective display. The pixel 802 is composed of three sub-pixels of red 804, green 806, and blue808 positioned side-by-side on a color filter. For a given pixel, one third of its area is generally allocated to each of the three sub-pixels that represent each of the three primary colors. Each sub-pixel toggles between black and its designated color. White is realized by activating all three sub-pixels. Because the sub-pixels are smaller than minimum dimensions distinguishable by the human eye, a color mixing effect is produced, and the pixel appears to be white. Each sub-pixel reflects only a portion of the incident light with wavelengths falling within a range of wavelengths that include the RGB primary represented by the sub-pixel. As a result, on average, the pixel reflects only one third of the light impinging on the pixel.

Figure 8B shows RGB sub-pixels of a pixel that reflects a saturated red color in a reflective display. For a pixel to realize fully saturated red, the red sub-pixel 810 reflects red and the green and blue sub-pixels 812 and 814 are non-reflective, as shown in Figure 8B. As a result, one third of fully saturated red is mixed with two thirds of black.
In temporal color dithering, there is no need to divide a pixel into sub-pixels to achieve the color mixing effect. Instead, primary colors are produced sequentially by the pixel during a short time period, referred to as a "frame." In order to drive the display of different primary colors within a frame, the frame is subdivided into sub-frames, each sub-frame corresponding to a primary color. Thus, each frame has as many sub-frames as the system has different primary colors. Figure 9A shows a pixel that reflects white using temporal color dithering in a reflective display. For a system that uses red, green, and blue primary colors, there are three sub-frames within each frame to accommodate each of these three primary colors. To realize white, each of the primary colors is reflected sequentially during the frame period, one primary color in each sub-frame. Red is reflected during a first sub-frame, green is reflected during a second sub-frame, and blue is reflected during a third sub-frame. The frame rate is sufficiently fast that human eye does not perceive each different primary color produced during a sub-frame, but instead perceives a color that results from mixing the primary colors. Reflection of a particular primary color can be achieved by many different technologies, one of which is based on optical interference and is described, in detail, in the following section. Because each sub-frame is dedicated to one of the primary colors, the other two primary colors in the incident light are not reflected during each sub-frame period. For example, the first sub-frame is dedicated to red, and blue and green primaries are not reflected.

Figure 9B shows a pixel that reflects a saturated red color using temporal color dithering in a reflective display. For a pixel to realize fully saturated red, red is reflected during the dedicated red sub-frame and no reflection occurs in the sub-frames dedicated to green and blue. Hence again, as in spatial color dithering, only a third of the incident light is reflected, on average, resulting in a generally dim display.

The RGB primaries are convenient for mixing colors for emissive and transmissive displays, but, since each pixel is divided into three sub-pixels, the efficiency of reflection is low on a per-pixel basis. The low efficiency is not apparent in emissive/transmissive displays because the intensity of emissive light sources can be sufficiently increased to provide bright displays when ambient light is relatively
weak. But the low efficiency becomes problematic in reflective displays because there is no backlight in reflective displays.

**Full-Spectral Interferometric Modulator**

Microelectromechanical-system (MEMS) based reflective display technologies have been under development for over a decade and have recently started to gain acceptance in the market. Some reflective-display technologies use interferometric modulation that is based on a Fabry-Perot Interferometer ("FPI"). Figure 10 is a side view of an FPI. The FPI has two parallel mirrors, a top mirror 1002 and a bottom mirror 1004. The mirrors are commonly produced by coating a transparent or semi-transparent substrate 103 with a reflective material. The two parallel mirrors are separated by a cavity 1006. Incident light beam 1008 enters the FPI from an incident side, travels through top mirror 1002, experiences multiple reflections between the two mirrors 1002 and 1004, and exits from the cavity as transmitted light beams 1010 and reflected light beams 1012 from the bottom mirror and the top mirror, respectively. Depending on the depth of the cavity 1006 and angle of incidence $\Theta$ 1013, the light exiting the FPI generally experiences either constructive or destructive interference.

For the exemplary FPI shown in Figure 10, the refractive index of cavity 1006 is less than that of the mirror-coated media 1003. A primary reflected beam 1009 from top mirror 1002 experiences phase inversion when the mirror is metallic film or coating. Light transmitted through the top mirror 1002 is incident on the bottom mirror 1004, and splits into transmitted components 1010 and reflected components 1012. The reflected light beam 1012 comprising the reflected components experiences phase inversion upon its reflection from the bottom mirror 1004, travels back through cavity 1006, and joins the primary reflected beam 1009. The primary reflected beam 1009 and the reflected beam 1012 are in phase when the following relationship is satisfied for gaseous media:

$$\lambda = 2d \cos \Theta$$

where $\lambda$ is the wavelength of the incident light; $d$ is the cavity depth; and $\Theta$ is the angle of incidence. Therefore, light of a specific wavelength experiences full constructive interference on the reflective side when the round-trip length through the
cavity is equal to an integer multiple of that wavelength. On the transmission side, however, the transmitted light beam 1010 of the same specific wavelength comprising transmitted components experiences fully destructive interference when the above relationship is satisfied. As a result, the mirrors and cavity act as a filter that reflects light of a specific wavelength through the device, and transmits light of other wavelengths. By controlling the depth of the cavity 1006 and the angle of incidence, the state of the interferometer can be changed, with each state corresponding to a different reflective color. For the sake of simplicity, in the following discussions, it is assumed that the incident light is perpendicular to the top mirror. For example, when the cavity depth equals half of the wavelength of red light and the incident light is perpendicular to the top mirror, the FPI reflects light of a red color and transmits light of a cyan color. Similarly, when the cavity depth equals 225 nm, half of the wavelength of blue light, and the incident light is perpendicular to the top mirror, the FPI reflects light of a blue color and transmits light of a yellow color.

When the cavity depth is greater than or equal to a first threshold value and less than 190 nm, corresponding to half of the wavelength of ultraviolet, most of the visible light destructively interferes, resulting in no reflected visible light, so that the display appears black. Black can also be generated by controlling the FPI to reflect light of infrared wavelengths, which are not visible to human eye. White is generated when the cavity depth is less than or equal to a second threshold value that is less than the first threshold value. White can also be generated when the two mirror are far apart relative to visible-light wavelengths, for example, greater than 1500 nm. When the cavity depth is greater than the second threshold value and less than the first threshold value, a gray color may be generated. The values of the first and second threshold may vary in different FPIs, depending on the angle of incidence and other factors.

Interferometric modulators using three RGB sub-pixels are known in the market. But like other RGB-based reflective color displays, interferometric modulators using RGB primaries are subject to the previously described problem of low reflectivity.

In an alternative approach to reflective display, spectral or monochromatic colors may be generated in place of RGB primary colors. Interferometric modulators using a single full-spectral pixel can reflect any spectral
color and can improve reflection efficiency by eliminating the need for sub-pixels. The cavity depth of the full-spectral interferometric modulator can be adjusted according to the dominant wavelength of a desired color. The entire surface area of the full-spectral pixel associated with the interferometric modulator can then be used to reflect the spectral color associated with the dominant wavelength. As a result, the pixel achieves 100% reflectivity and appears three times brighter than a pixel that generates an equivalent color by mixing RGB primaries.

Interferometric modulators capable of reflecting spectral colors are difficult to manufacture due to the need for stringent fabrication precision. The two reflective layers in the interferometric modulator need to be strictly parallel when the modulator is both actuated and unactuated. Any tilting of the mirror surface will lead to rainbow stripes on the modulator and a generally gray appearance.

An interferometric modulator that maintains a parallel orientation between the mirrors has been recently developed. This new type of interferometric modulator is referred to, below, as a self-parallelizing interferometric modulator ("SPIM"). Even though the depicted pixel in this example is squared, it can also be of different shape, such as circular, hexagon, and triangle. Figure 11A is an isometric view of the SPIM and Figure 11B is an exploded view of the SPIM. The SPIM 1100 has a transparent fixed plate 1102, a movable plate 1104, and a bottom control plate 1106. The fixed plate 1102 faces the full-spectrum incident light 1108 on one side and has a semi-reflective mirror coating on the other side. The movable plate 1104, with a mirror on its top side, is coated or formed with an electrically conductive film. A distance between the fixed plate 1102 and the movable plate 1104 defines the depth of cavity 1110, which is used to modulate light transmitted into the cavity. The bottom control plate 1106 underneath the movable plate 1104 is coated with an electrode that faces upwardly and may be patterned in a plurality of areas that can be independently provided with voltages to enable anti-tiling compensation of the movable plate. A plurality of spring beams 1112 and 1114 are anchored to a plurality of supporting fixed posts 1116 and 1118. The supporting fixed posts provide support to suspend the movable plate 1104 through the spring beams to a particular vertical position when the movable plate 1104 is driven.
The movable plate 1104 is actuated by applying voltages to the plurality of electrodes disposed on the bottom plate and the electrically conductive movable plate. Conductors or drivers are coupled to the electrodes on the bottom plate and to the movable plate and are configured to be coupled to a controlled voltage source in order to enable predefined voltages to be applied to each of the electrodes. In certain implementations, the bottom control plate 1106 includes three spaced-apart electrodes 1120, 1122, and 1124, shown in Figure 11B. When voltages are applied to electrodes 1120-1124 to actuate the movable plate 1104, the movable plate moves downwardly, increasing the cavity depth 1110. When the spring beams 1112 and 1114 are perfectly balanced and when voltages applied to electrodes 1120, 1122, and 1124 are identical, the movable plate 1104 remains parallel to the fixed plate 1102. Any tilting can be eliminated by applying different voltages to the electrodes in order to compensate for the mechanical imbalance. The compensating voltages may be determined after the modulator has been fabricated and included in a display and then subsequently applied driving display operations.

Referring to Figure 11B, when three electrodes are disposed on the bottom control plate, three thin-film transistors ('TFTs') 1126, 1128, and 1130 may be used for active-matrix addressing to actuate the SPIM. The three electrodes 1120, 1122, and 1124 are connected to three data lines 1132, 1134, and 1136 and one gate line 1138 through the three transistors 1126, 1128, and 1130. Figure HC shows a cross-section view of a TFT used in the SPIM. The TFT comprises a gate 1140, a gate insulating layer 1142, a semiconductor layer 1144, a source 1146, and a drain 1148. The TFT can be switched on by applying a voltage to the gate 1140 connected to the gate line 1138. Once the TFT is switched on, a data voltage is applied to the source 1146 and transferred through the drain 1148 from one of the data lines 1132, 1134, and 1136 to one of the electrodes 1114, 1116, and 1118. Application of an appropriate predefined voltage to each of the three data lines 1132, 1134, and 1136 that are connected to each of the three electrodes 1114, 1116, and 1118 produces an electrostatic attraction that vertically moves the movable plate 1104, changing the depth of the cavity 110.

Figure 12A illustrates a cross-section view of the SPIM when the movable plate is not actuated. Figure 12B illustrates a cross-section view of the SPIM
when the movable plate is actuated. In Figure 12A, the top fixed plate 1102 and the movable plate 1104 are in contact with each other when the SPIM is not actuated and in its un-driven state, so that the modulator reflects no visible light. When the modulator is actuated or driven, as shown in Figure 12B, cavity 1110 is formed between the two plates, and the depth of this cavity determines the wavelength of light reflected by the modulator. The elements of the modulator rest on the two supporting fixed posts 1116 and 1118 attached to the top fixed plate and to the bottom plate 1106. The movable plate 1104 is maintained parallel to the fixed plate 1102. When the movable plate 1104 is actuated by applying a voltage 1202 to the electrodes on the bottom control plate 1106 and the movable plate 1104, an electrostatic force pulls the movable plate 1104 away from the fixed plate 1102 and toward the bottom control plate 1106. The depth of the cavity 1110 is controlled by the level of the applied voltage and the restoring force provided by spring beams 112 and 114 of the movable plate. The spring beams act as springs that pull the movable plate 1104 back to its original un-driven state when the voltage is no longer applied to the electrodes.

Since each modulator is a full-spectral pixel, the entire pixel area can be used to reflect a color, thus greatly increasing the reflection efficiency. Colors along the spectral locus shown in the chromaticity diagram in Figure 7 can be produced by controlling the movable plate of the SPIM to reflect a color of a particular wavelength. Colors along the line of purples can be produced by mixing a reflected blue and red. To depict a color with less lightness and saturation, spectral colors may be blended with a fraction of white and black. Thus, different proportional combinations of a spectral color, black, and white components can be used to produce the full spectrum of colors in the chromaticity diagram. By replacing RGB primaries with a new set of color-model components, namely a spectral color along the spectral locus, black, and white, to drive the SPIM, the reflection efficiency is increased and the color gamut can be substantially extended to cover an area in the chromaticity diagram not previously realizable using a RGB color model.

The movable plate in the SPIM can be controlled to occupy various positions to generate spectral colors continuous in wavelength. The visible spectrum in the range of [400nm, 700nm] may be divided into N levels, also called the levels of hues. The division may be evenly or unevenly distributed over the wavelength range.
Alternatively, colors may also be digitized into a number of discrete levels. The number of discrete levels of spectral color should be properly selected in order to optimize the color performance of a reflective display and to minimize processing overheads. An ideal number of levels allows for a wide range of colors while still minimizing the number of bits needed to represent each color. In certain implementations, a 5-bit digital encoding is selected to represent the analog wavelength from 400 nm to 700 nm. To convert the continuous analog wavelength to a digital 5-bit representation, the wavelength range [400,700] is partitioned into $2^5$ or 32 discrete levels with a step size, also called resolution $r = 700-400/2^5$ that defines the smallest analog change resulting from changing one bit in digital number. In other implementations, a 10-bit digital encoding is selected to represent the analog wavelength from 400 nm to 700 nm, resulting in $2^{10}$ or 1024 discrete levels with a resolution $r = 700-400/2^{10}$.

Color Generation Using One or More Spectral Colors, Black, and White

A new color model is introduced in this section and used as a basis to drive the SPIM described in the previous section. In this color model, a given non-purple color is represented by three color components: a spectral color, black, and white. The new-color-model coordinates of the given non-purple color contain four values: the wavelength associated with the spectral color $x$, a percentage of the spectral color $P_s$, a percentage of black $P_b$, and a percentage of white $P_w$. Alternatively, one of the percentages may be omitted from the coordinate system as the sum of the three percentages is 1.0. Different proportional combinations of a chosen spectral color, black, and white can produce the entire spectrum of colors in the chromaticity diagram except purple colors. Purple colors can be represented by combinations of four color components: blue, red, black, and white. The new-color-model coordinates for a given purple color also contain four values: a percentage of blue $P_b$, a percentage of red $P_r$, a percentage of black $P_k$, and a percentage of white $P_w$. The sum of $P_b$, $P_r$, $P_k$, and $P_w$ is equal to 1.0.

Images and videos input to a SPIM-based reflective display generally needs to be transformed from RGB encodings to encodings that use the color coordinates of the new color model. As one example, the encoding may encode pixel
color values as quadruple values of a wavelength of a spectral color, a percentage of the spectral color, a percentage of black, and a percentage of white. Because of many years of development of CRT, plasma, LCD, and other light emissive and transmissive displays, video and image data is generally encoded in a RGB color model for electronic display and in cyan-magenta-yellow ("CMY") for hardcopy devices. Therefore, input data generally needs to be transformed from a device-dependent color model defined by primary color components, such as RGB, to the new color model in order to drive a SPIM-based display.

Figure 13A is a diagram illustrating a 24-bit RGB representation of a pixel and a 32-bit representation of a pixel in the new color model. The 32-bit here is for illustrative purposes and the number of bits should be minimized to balance the color resolution and performance. The upper encoding 1302 represents a pixel using a total of twenty-four bits that are segmented into a lower 8-bit portion 1304, a middle 8-bit portion 1306, and an upper 8-bit portion 1308. Eight bits are allocated for each of the three red, green, and blue component values, which together represent the color of the pixel. For example, a fully saturated shade of red is represented when the eight bits of the red component in the upper 8-bit portion are ones and the eight bits of the green and blue components in the middle and lower 8-bit portions are zeros. The lower encoding 1310 represents a pixel in the new color model using a total of thirty-two bits of storage. In one implementation, the 32 bits of storage are segmented into three 7-bit portions 1312, 1314, and 1316, a 10-bit portion 1318, and a 1-bit portion 1320. In order to achieve an adequate number of color intensity levels, seven bits of data are used to represent each percentage coordinate of the new-color-model coordinates. The first 7-bit portion 1312 is allocated for the percentage value of black $p_k$ and the second 7-bit portion 1314 is allocated for the percentage value of $p_w$. The 1-bit portion 1320 is a flag bit indicating whether or not the pixel corresponds to a purple color. When the pixel does not correspond to a purple color, the third 7-bit portion 1316 from bit 14 to bit 20 is allocated for the percentage value of a spectral color and the 10-bit portion 1318 from bit 21 to bit 30 is allocated for the wavelength value of the spectral color. When the pixel represents a purple color, the third 7-bit portion 1316 from bit 14 to bit 20 are allocated for the percentage value of red and another seven bits from bit 21 to bit 27 within the 10-bit portion are allocated for the
percentage value of blue. The upper three bits, from bit 28 to bit 30, of the 10-bit portion are filled with zeros.

Figure 13B is a diagram illustrating a color coordinate conversion from the 24-bit RGB representation to the 32-bit representation in the new color system using a fully saturated shade of red as an example. A fully saturated shade of red is represented in a 24-bit pixel 1322 in which the eight bits of the red component in the upper 8-bit portion 1324 are ones and the eight bits of the green and blue components in the middle and lower 8-bit portions 1326 and 1328 are zeros. To convert the red color pixel from the 24-bit RGB encoding to the 32-bit new-model encoding, the wavelength of the red color pixel is determined to have a value of 650 nm. The percentage of the red spectral color has a value of 100, since the red color is fully saturated, and the percentages of black and white are both zero. By converting the analog values to digital values, the 24-bit fully saturated red can be represented in a 32-bit pixel (1330), in which the seven bits in the first and second 7-bit portions are zeros, the seven bits in the third 7-bit portion are ones, the 10-bit portion has bit values of ‘1101010101’, representing the 10-bit digital value of the wavelength, and bit 31 is 0, indicating that the color pixel is non-purple. The 10-bit digital value of the wavelength is calculated using the following equation:

\[ D\nu = (\lambda_{AV} - \lambda_{MIN}) / r \]

where \( D\nu \) is the digital value of the wavelength; \( \lambda_{AV} \) is the analog value of the wavelength, in this case, 650 nm; \( \lambda_{MIN} \) is the minimum wavelength value, in this case, 400 nm; and the resolution \( r \) is defined as 700-400/210.

The number of bits varies for different RGB encodings. Some devices may be configured to generate 24-bit color, while other devices may be configured to generate more or less than twenty-four bits of color. For a 24-bit RGB encoding, there are 256 shades of red, green, and blue, for a total of 16,777,216 possible colors that need to be transformed to the new color model. For an 8-bit RGB encoding, there are a total of 256 possible colors that need to be transformed. The transformation may be performed analytically based on mathematical expressions. Alternatively, the transformation may be performed empirically based on color-matching experiments or semi-empirically by applying adjustments to values computed from mathematical expressions. The output values of the transformation may be stored in the form of a
color look-up table when a display panel is placed into operation. Input encodings are used as indexes or addresses for accessing equivalent new-model encodings in the look-up table. The data stored at each address in the table is the output value of the coordinate transformation when the input variables have values equal to the value of the address.

Figure 14 provides an exemplary color look-up table. The color look-up table 1400 contains one column 1402, representing a set of 32-bit coordinate encodings in the new color model. Each entry in column 1402 corresponds to a color in the RGB color model. For example, a color pixel with index value S represents a red component with bits 11111111, a green component with bits of 00000000, and a blue component with bits of 00000000 in the 24-bit RGB format and corresponds to a 32-bit transformed new-model encoding shown in table cell 1404. The number of entries contained in the color look-up table varies depending on the bit depth of the input color model.

Figure 15A shows a conversion from RGB coordinates to the new-model color coordinates using a HSL color model as an example. A detailed implementation is given below, with reference to Figure 15A, to describe how the wavelength of a spectral color and percentages of various color components are determined for a given color represented by a 24-bit RGB encoding. The HSL color model previously shown in Figure 3 is used as an example in order to demonstrate how the coordinate transformation is performed. However, many other color models can be used for the coordinate transformation, including the CIE XYZ color model or the CIE LUV color model. The coordinates for a particular color in the 24-bit RGB color model, \( \{r,g,b\} \), can be converted to the coordinates of the color in the HSL color model, \( \{h,s,l\} \), using previously described equations (1) to (3). For example, color point C1502 in the HSL color model 300, with coordinates \( \{h_c,s_c,l_c\} \), corresponds to point C’1504 in the RGB color model 1506. The percentage of hue is defined as:

\[
P_s = \sqrt{1.00 - 2x} \cdot d' \neq 0, \quad x \in (0,0.5)
\]

\[
P_s = 0, \quad d' = 0
\]

where \( d' \) is the distance from point C to the central vertical axis 312; \( d'' \) is the length of a horizontal line passing through point C from the central vertical axis 312 to the
surface of the bi-pyramidal prism 300; and x is the vertical height of point C with respect to the plane 324 that includes the origin 313 and fully saturated colors 302, 304, and 306. The percentage of white is defined as:

\[ P_w = \frac{341.00 - 2x}{l_c} \times l_c \quad x \in (0, 0.5) \]

where \( l_c \) is the lightness. The percentage of black is defined as:

\[ P_b = \frac{d(1.00 - 2x)(1 - l_c)}{d^* l_c} \quad l_c \in (0, 1.00) \]

The sum of \( P_s, P_w, \) and \( P_b \) is equal to 1.0.

When the percentage of hue \( P_s \) is not equal to zero and the hue of point C, defined by angle \( \Theta \) 316, falls in the range of \([0°, 240°]\), the dominant monochromatic wavelength of the hue can be determined and corresponds to the wavelength of a spectral color. There are different approaches to determine the dominant monochromatic wavelength, \( \lambda \), of the given color point C in the HSL color model or point \( C' \) in the RGB color model. In one implementation, the dominant wavelength is derived from angle \( \Theta \) of color point C in the HSL color model. The dominant wavelength \( \lambda \) is determined by color-mapping hues in the range \([0°, 240°]\) to a spectral wavelength between 700 nm and 450 nm. The color mapping may be performed using one or more wavelength-hue look-up tables. Figure 15B provides an exemplary wavelength-hue look-up table for hues in the range of \([0°, 240°]\). Hue is used as an index into the look-up table, and the data entry stored at each index in the table is the wavelength value of the corresponding hue. For example, index 0 corresponds to a wavelength of 700 nm, index 120 corresponds to a wavelength of 550 nm, and index 240 corresponds to a wavelength of 450 nm. The wavelength in the wavelength-hue look-up table may be determined using an analytical color operator \( f(0) \) applied to the hue or determined empirically or semi-empirically.

For non-spectral hues in the range of \([241°, 359°]\), which are hues that cannot be represented by a single wavelength, but are instead generated as a mixture of blue and red, a blue ratio, \( f \), is determined and mapped to each non-spectral hue. The blue ratio, \( f \), is defined as:

\[ f = \frac{0-240}{120} \]
Figure 15C provides an exemplary ratio-hue look-up table for non-spectral hues. Again, hue is used as an index to the look-up table, and the value stored at each index in the table is the blue ratio of the corresponding hue. The look-up table is indexed by hue in the range of [241°, 359°]. For example, index 241 corresponds to a blue ratio of 0.99, while index 359 corresponds to a blue ratio of 0.01. The percentage of blue \( P_b \) and the percentage of red \( P_r \) are calculated from the blue ratio as follows:

\[
\begin{align*}
P_b &= f \times P_s \\
P_r &= (1-f)P_s
\end{align*}
\]

Similar to the wavelength, the blue ratio may be determined using an analytical color operator \( f' \) (or \( f'' \)) applied to the hue or determined empirically or semi-empirically.

In alternative implementations, the chromaticity diagram shown in Figure 7 may be used to determine the dominant wavelength associated with the hue. The color point \( C' \) in the RGB color model is transformed to a corresponding color point \( C'' \) in the CIE chromaticity diagram by converting the \((r,g,b)\) coordinates to the \((x,y)\) coordinates using previously described equations (4)-(8). Using the approach previously described with reference to Figure 7, the dominant wavelength of the given color \( C \) is determined as the wavelength associated with an intersection point on the spectral locus when the interaction point falls on the spectral locus. When the intersection point falls on the line of purples, a blue ratio for the purple color is calculated.

Figure 16 shows a flow chart for a routine that prepares the color look-up table, using the HSL model as an example. In step 1602, the routine receives an indication of a RGB color model, for example, a 24-bit RGB color model. A look-up table with \( x \) entries is allocated and initialized in step 1604. In the \textit{for}-\textit{loop} of steps 1606-1628, for \( i \) from 0 to \( x \), the \( r, g, b \) values are extracted, in step 1608, from the current value of \( i \) and converted to the \( h, s, l \) values in the HSL color model, in step 1610. In step 1612, the percentages of hue, \( P_s \), black \( P_b \), and white \( P_w \) are calculated. Decision block 1614 determines whether or not the hue of \( i \) falls in the range of \([0,240]\). When the hue of \( i \) is in the range of \([0,240]\), control flows to step 1616 in which the dominant wavelength \( \lambda \) of the hue is extracted from one or more wavelength-hue look-up tables when \( P_s \) is not equal to zero or the dominant
wavelength $\lambda$ is set to zero when $P_3$ is zero. In step 1618, the routine packages the wavelength $\lambda$ and the three percentages $P_r^{3/4}$ and $P_w$ into a 32-bit integer $t$ and stores $t$ at a table entry with index $i$. When the hue of $i$ is not in the range of [0,240], control flows to step 1620 in which the blue ratio/of the hue is extracted from one or more ratio-hue look-up tables. The percentages of blue $P_b$ and red $P_r$ are calculated in step 1622. In step 1624, the routine packages the four percentages $P_b$, $P_r$, $P_k$, and $P_w$ into a 32-bit integer $t$ and stores $t$ at a table entry with index $i$. Decision block 1626 determines whether or not $i$ is equal to $x$. When $i = x$, the routine terminates. Otherwise, control flows to step 1608 to process the next color point with value $i = i + 1$.

Various color dithering algorithms, such as spatial dithering, temporal dithering, or a combination of both, can then be used to mix color components, which are one or more spectral colors, black, and white, to produce any desired color. In certain implementations, when the temporal dithering method is used, a desired non-purple color can be dithered from sequencing a spectral color associated with a dominant wavelength, black, and white for certain durations over a frame period of $T$. The durations for the spectral color, black, and white can be determined from the percentage of each color component, respectively. For example, the duration of the spectral color, $t_\lambda$, is calculated by multiplying the frame period $Th$ by the percentage of the spectral color $P_\lambda$. The duration of black, $t_b$, is calculated by multiplying the frame period $T$ by the percentage of black $P_b$. Similarly, the duration of white, $t_w$, is calculated by multiplying the frame period $T$ by the percentage of white $P_w$. The durations of black and white define the saturation and lightness of the color, while the spectral color defines the hue. In the color generation process, a pixel switches and resides in its first color state for a specific duration, then switches and resides in its second color state for a specific duration, and finally switches and resides in its third color state until the frame period elapses. The order of sequencing the three color components may be altered among different frame periods to mitigate any possible motional color-breakup problems. The color state of each pixel is controlled by the cavity depth in the SPIM which is, in turn, controlled by the applied voltages, in order to reflect the spectral color, black, and white. Since the color components need to be combined to generate the desired color, the modulators generally have a very high
response speed to switch from one color state to another. When pure white is desired
to be reflected from a pixel, the pixel reflects full incident light during the entire
frame period. To generate a color with 100% saturation, the dominant wavelength
associated with the spectral color is reflected uninterruptedly during the entire frame
period.

In other implementations, a spatial dithering method may be used to
mix one or more spectral colors, black, and white. Spatial dithering divides a pixel
into many smaller addressable sub-pixels and separately drives the individual sub-
pixels in order to obtain gray scales of a particular color. Each sub-pixel is a discrete
SPIM and switches from one color component to another by varying the depth of the
SPIM cavity to reflect a spectral color, black, or white. A number of grayscale levels
for a desirable color may be displayed by each individual pixel by varying the
percentages of the three color components.

Figure 17 shows a spatial dithering scheme that divides a pixel into 4
sub-pixels. A pixel can be divided into any number of sub-pixels. When a pixel 1702
is divided into 4 sub-pixels 1704, 1706, 1708, and 1710, each pixel 1702 is capable of
producing ten gray scale levels for each of spectral colors. For example, a pixel 1712
having a scale of 100% of the spectral color, 0% of black, and 0% of white may be
perceived as a color with maximal intensity, while a pixel 1714 having a scale of 25%
of the spectral color, 75% of black, and 0% of white may be perceived as a color with
the minimal intensity. The number of sub-pixels per pixel, e.g. 4 bits, may be
referred to as the bit of gray scale resolution.

In alternative implementations, a hybrid color dithering method can be
achieved using combinations of temporal and spatial dithering methods. Using the
spatial dithering scheme shown in Figure 17 as an example, each of the spatially-
mixed sub-pixels within a pixel can be subdivided into sub-frames, each sub-frame
corresponding to one of the color components that make up a color. The time
durations associated with each sub-frame over a frame period may be varied to
generate a spectrum of gray-scale levels. Hybrid color dithering displays can be
designed to increase the number of gray scales and to maximize color depth while
maintaining satisfactory color and spatial scales. In addition, the response speed
requirement for the SPIM is not as high in spatial dithering as for the temporal
dithering. By combining spatial dithering with temporal dithering, the display does not need to be refreshed as often as when temporal dithering is used alone.

A System for Controlling a Reflective Display Panel

Figure 18 is a schematic display image frame. An image to be processed 1800, for example, a bmp picture file, is received, represented as an \( m \times n \) dimension array, with each dot representing a pixel. PiXell802 has display coordinate (1,1), pixell806 has display coordinate \((n,m)\), and each pixel has a pair of coordinate \((i,j)\) with \(i\) indexing the row and \(j\) indexing the column of the \( m \times n \) array. Each pixel in the image is associated with a quadruplet, for example, a wavelength of a spectral color and percentages of the spectral color, black and white for non-purple colors and percentages of blue, red, black and white for purple colors. For example, a non-purple pixel 1802 is associated with \((\lambda_1, P_{\lambda_1}^s, P_{\lambda_1}^w, P_{\lambda_1}^k)\), another non-purple pixel point 1804 is associated with \((\lambda_2, P_{\lambda_2}^s, P_{\lambda_2}^w, P_{\lambda_2}^k)\), and purple pixel point 1806 is associated with \((\lambda_3, P_{\lambda_3}^s, P_{\lambda_3}^w, P_{\lambda_3}^k)\). When a temporal-dithering method is used to mix the color components, the percentage color coordinates associated with each pixel can be converted into time durations over a frame period. For example, pixel 1802 is associated with color coordinates \((\lambda_1, t_{\lambda_1}^s, t_{\lambda_1}^w, t_{\lambda_1}^k)\) and pixel 1806 is associated with color coordinates \((\lambda_3, t_{\lambda_3}^s, t_{\lambda_3}^w, t_{\lambda_3}^k)\). Each pixel in the image may be a SPIM, as shown in Figure 11. In cases when spatial dithering is used, each pixel is divided into a number of sub-pixels 1808, for example four sub-pixels, with each sub-pixel implemented as a SPIM. A full-image display is rendered by spatially assembling a plurality of SPIMs in rows and columns on a substrate layer, each reflecting a particular color. Appropriate predefined voltages are sequentially applied to the electrodes of each SPIM to vary the cavity depth of the SPIM in order to reflect a spectral color of a certain wavelength.

Calibration and color correction processes are required for a reflective display panel to reflect a consistent color gamut. The reflected color gamut is sampled and analyzed to determine voltages that need to be applied to the electrodes of each pixel to achieve a desired color. Using the SPIM shown in Figure 11 as an example, to reflect a particular color, there are potentially three voltages that need to
be applied to three electrodes on the bottom control plate. A series of voltage combinations is applied to each SPIM to establish a voltage-wavelength relationship between the applied voltages and the wavelength reflected by that SPIM. Alternatively, a common voltage-wavelength relationship may be used to represent a group of SPIMs due to the fact that SPIMs on a display panel are subject to similar manufacturing conditions. The voltage-wavelength relationships for each different group of SPIMs may be stored and indexed in one or more voltage-wavelength look-up tables in a driver circuit, a control unit, or the memory of a host device for use in driving the display panel. The stored voltage data is referenced both for color realization and tilt correction.

Figure 19 shows a diagram of a signal processing circuit of a reflective display panel. In one implementation, the signal processing circuit of the reflective display panel shown in Figure 19 consists of a control unit 1904, a voltage generator 1906, a row driver 1908, a column driver 1910, and a pixel matrix 1912. For clarity of illustration, the pixel matrix 1912 contains only three adjacent rows and three adjacent columns of SPIMs, which provides nine unit pixels. A unit pixel may correspond to a pixel or to a sub-pixel when pixels are further divided into sub-pixels. The signal processing circuit receives an electrical video/image signal having a standard format, such as a 24-bit RGB format. The received signal is transmitted to the control unit 1904 in which the signal is transformed from the 24-bit RGB coordinates to 32-bit coordinates in the new color model. The transformation is made by using one or more color look-up tables 1914. The control unit 1904 determines the dithering method to be used and color coordinates that need be produced for each unit pixel in the display, and generates timing and voltage signals to control the voltage generator 1906. The voltage generator 1906 is controlled by the control unit 1904 in accordance with a predefined voltage-wavelength relationship table 1916 to apply appropriate voltages to row and column drivers 1908 1910 of the display. The row and column drivers drive the display panel to display images. The pixel matrix 1912 is horizontally connected to the row driver 1908 through data lines and vertically connected to the column driver 1910 through gate lines. Each unit pixel in the pixel matrix is controlled by an SPIM containing a plurality of electrodes connected to a gate line and at least one data line through one or more TFTs. In certain
implementations, three data lines are needed in order to maintain the movable plate parallel to the top plate and to eliminate tilting of the movable plate of the SPIM, as previously discussed. For example, unit pixel 1918 in the pixel matrix is controlled by an SPIM containing three electrodes connected to gate line G1 and three data lines D11, D12, and D13 through three TFTs I920. The row driver I908, also called the gate driver, is operated to generate a gate pulse along a gate line, controlling one row of unit pixels at a time by turning "ON" or "OFF" the TFT switch of every unit pixel in that row. For example, when row 1922 is selected and the TFT switches in row 1922 are turned on, the column driver I910, also called the data driver, delivers voltage signals through data lines D11, D12, D13, D21, D22, D23, D31, D32, and D33 and applies the voltages simultaneously to all columns to charge each unit pixel in row 1922 to a desired voltage. Next, the TFT switches in row 1922 are turned off, and the succeeding row 1924 is selected and the TFT switches in row 1924 are turned on. The column driver 1920 delivers another set of voltage signals through data lines and applies data voltages to unit pixels in row 1924. Similar to an active-address LCD, unit pixels in the reflective display are scanned line by line. By scanning the gate lines sequentially and by applying data voltages to the data lines in a specified sequence, every unit pixel on the reflective display panel can be addressed and charged to a desired voltage.

When temporal dithering is used to mix the three color components, a frame period can be divided into a number of time slices to synchronize with the horizontal scan rate and to allow a color image to be generated with varying intensities or grayscale levels. The number of time slices may vary for various applications. For example, in a frame that is divided into 2^n-1 time slices, an SPIM may generate up to 2^n possible levels of gray scale for each of the pixels, corresponding to 2^n different intensities or shades of a particular color.

Figure 20 illustrates a control-flow diagram for processing video/image signal using the reflective color display technology disclosed in the current document. The control-flow diagram shows the image processing steps in one frame period using temporal dithering technique as an example. In one implementation, a video or image input signal in one or more standard encodings, such as composite encodings, S-Video encodings, HDMI encodings, or other encodings, is
received, in step 2002, and decoded and initially processed by the signal processing circuit system of a display device, in step 2004, to transform the input signal to a first common signal encoding, for example, the 24-bit RGB encoding. In step 2006, the input signal is further processed by the signal processing circuit to transform 24-bit RGB coordinates to 32-bit coordinates in the new color model and subsequently to the time durations within a certain frame period. In step 2008, the control unit of the signal processing circuit maps color coordinates \((\lambda, t_p, i_o, \gamma)\) or \((\lambda, t_p, t_o, t_i)\) for each pixel. As noted above, the control unit can use various color dithering methods, such as the spatial dithering, temporal dithering, or a combination of both, to produce any desired color at each pixel. The temporal dithering technique is used as one example in the control-flow diagram. When the control unit specifies a color for each pixel, a voltage generator or the control unit obtains voltage data from one or more predefined voltage-wavelength look-up tables in step 2010, and the voltage generator applies the obtained voltage data to row/column drivers of the display device in step 2012. In the \(7/4\)r-loop of steps 2014-2024, for each row of pixels, the row driver turns on the TFT switches on the selected row in step 2016. In step 2018, the column driver applies data voltages obtained from the voltage-wavelength relationship table to pixels on the currently selected row. In response to the applied voltage, the cavity depth of the SPIM associated with each pixel on the currently selected row is adjusted to a particular value to reflect a particular color. Next, the row driver de-activates the currently selected row in step 2020 and moves to the next row in step 2022. Decision block 2024 determines whether or not more rows in the pixel matrix are available for scanning. When more rows are available, control flows back to step 2014. Otherwise, control flows to decision block 2026 to determine whether or not the current frame period has elapsed. When the current frame period has elapsed, the routine terminates. Otherwise, control flows to step 2028, in which the row and column drivers return to drive the first row in the pixel matrix. Control then returns to step 2012 to start a new time slice within the current frame period.

**SPIM-based Reflective Label**

As discussed in preceding subsections, self-parallelizing interferometric modulators ("SPIMs") can be arranged into arrays to produce
reflective color display panels. In many implementations of such reflective display panels, each SPIM corresponds to a pixel, with applied voltages varying the cavity depth of each SPIM so that each SPIM reflects a particular wavelength of light corresponding to the color assigned to the pixel at a particular instant in time. Reflective display panels are suitable and desirable display devices for a wide range of stationary and mobile electronic processor-controlled devices and systems, from desktop computers to cell phones.

Tags and labels represent another set of devices amenable to SPIM-based implementations. Tags and labels may be used in retail environments to physically associate a price with items for sale. Tags and labels may also be used in a variety of additional environments and applications, including labeling of laboratory samples in order to associate patients with samples, labeling of equipment in research laboratories, labeling and marking components and systems during manufacturing processes, and labeling containers and vehicles to indicate their contents, owners, and other such attributes.

Printed and adhesive labels are frequently used in a variety of different environments and applications and have advantages and familiarity, low cost, and ease of production. Printed labels, however, are generally one-use labels. For example, labels used to mark prices of items in a retail environment cannot be subsequently changed to reflect new pricing, discounts, and other price changes. Instead, the labels either need to be replaced or physically modified by lining-through or blacking out the original printed prices and writing new prices in empty spaces on the labels or by affixing new price labels to the original labels. Similar considerations apply to many different label applications and environments.

Light emitting displays, such as backlit LCD and LED displays, can be used labeling and tagging, but they are bulky and use significant amounts of energy. In addition, they need to operate to produce displays that are brighter than ambient light in order to be functional. By contrast, SPIM-based reflective labels perform well at locations where ambient light is bright, such as in outdoor daylight. They can be easily electronically controlled to display different numeric prices, phrases, sentences, and other information at different times. Moreover, SPIM-based reflective labels may be used to display a wide variety of attractive, eye-catching colors,
designs, and temporally changing patterns. SPIM-based labels and tags have high reflectivity, as well. For these reasons, SPIM-based tags and labels represent an attractive new type of labeling and tagging technology for application in a wide variety of different tag-and-labeling environments.

Figures 21A-F illustrate several example SPIM-based reflective-label implementations and characteristics of those implementations. Figure 21A shows a first example SPIM-based reflective label. The SPIM-based reflective label 2102 is rectangular in shape and features five seven-segment digit displays 2104-2108 and a period or point display 2110. Each of the digit displays and the period or point display includes active segments or regions comprising two-dimensional arrays of SPIMs. Within the label, a flexible battery 2112 provides a power source for the logic and electronics that control reflectivity of the SPIMs. In addition, the SPIM-based reflective label includes a number of electrical contacts 2114-2119 that together comprise an input port for input of the information to be displayed by the label. In many implementations, the electronic control may be significantly less complex than the control used for reflective displays of processor-controlled devices such as personal computers and mobile phones. In certain implementations, for example, the SPIM display elements of each segment may all reflect a single wavelength of light, appear white, or appear black at each point in time. Thus, entire arrays of SPIMs may be collectively controlled, rather than being separately controlled, as in reflective displays of processor-controlled devices.

Figure 21B shows a second example of a SPIM-based reflective label. The second example of a SPIM-based reflective label 2130 also includes five digit displays 2131-2135 and a period or point display 2136. Similar to the first example label 2102, the second example label 2130 also includes a flexible battery 2138 to serve as a power supply for the logic and electronics that control reflectivity of the SPIMs within the digit and period or point displays. The second SPIM-based reflective label alternatively includes a radio-frequency-identification ("RFID")-like printed circuit 2140 that includes a radio-frequency antenna and simple logic circuitry to replace the electrical contacts. This radio-frequency device provides access to reflective label by complementary control wands or other control devices to allow
users to input numerals, prices, and other information for display by the SPIM-based reflective label.

Both rechargeable and non-rechargeable batteries may be used in SPIM-based reflective label. Alternatively, photovoltaic cell may provide power for a SPIM-based reflective label, in certain implementations, or, in other implementations, an RFID antenna provides the power source for charging a flexible rechargeable battery so that the power for driving the display can be self contained in the panel. Alternatively, as shown in Figures 21C-D, illustrating alternative implementations of the SPIM-based reflective labels shown in Figures 21A-B, connectors 2144 and 2146 may provide for connection of external batteries and other types of power sources to power the SPIM-based reflective labels.

Figure 21E illustrates the appearance of the example SPIM-based reflective label 2102 shown in Figure 21A as the SPIM-based reflective label displays a price of $76.89. As shown in Figure 21E, only the segments or regions of the digit displays and period or point display controlled to reflect non-background wavelengths, including segment 2150, are visible against the background of the SPIM-based reflective tag. The electrical contacts, battery, and non-activated segments all appear as a uniform background.

Because SPIM-based reflective displays consume little power and are electronically controlled, SPIM-based tags and labels can feature a variety of different dynamic display modes, with digits, letters, and other symbols changing color periodically and with textural information scrolling across the label as in a Times-Square marquee. Radio-frequency-controlled SPIM-based reflective displays and SPIM-based reflective displays with other types of communications interconnections with computers and other processor-controlled devices may be controlled to automatically change the information displayed by the labels. For example, a storewide 10-percent-off sale can be almost instantaneously reflected in displayed-price-information changes when SPIM-based reflective labels are used for labeling store inventory with prices.

Figure 21F illustrates the basic structure of a SPIM-based reflective label or tag. A SPIM-based reflective label or tag 2160 generally comprises three distinct layers 2162-2164. The top layer 2162 is often implemented as a transparent
polymer sheet with a semi-transparent reflective coating. This first, semi-transparent layer 2162 serves as the fixed plates of the SPIMs that together compose the reflective displays of the SPIM-based reflective label. A second polymer sheet 2163 serves as the movable plates of the SPIMs that together compose the information displays of the SPIM-based reflective label or tag. This second layer 2163, in certain implementations, has a metal coatings on one side and, in other implementations, has metal coatings on both sides. The distance between the lower surface of the first layer 2162 and the upper surface of the second layer 2163 defines the cavity depth for each SPIM. The second layer, although initially applied as a continuous sheet during initial fabrication steps, is cut into individual movable plates for individuals SPIMs within the display regions of the SPIM-based reflective label or tag. The bottom layer 2164 is a substrate patterned with electrodes and other logic and electronic circuits and acts as the control plates or driving plates within SPIMs as well as the overall logic and control for the SPIM-based reflective tag or label, including control of the battery power supply and interface to the electrical contacts or radio-frequency device. For many implementations, the layers are relatively thin, on the order of millimeters or microns, and flexible, so that the entire SPIM-based reflective tag or label is generally at least semi-flexible to facilitate a wide range of labeling and tagging applications.

Figures 22A-B illustrate the patterning and cutting of the middle layer (2163 in Figure 21D). A rectangular pattern, or grid, of post-like structures perpendicular to the plane of the SPIM-based reflective label or tag is first created by any of various techniques discussed, in detail, below. In Figure 22A, these posts are shown in cross-section as small squares, such as square 2202. The second layer (2163 in Figure 21D) is then cut, using stamping or various types of laser cutting, to form the movable plate of a SPIM 2204 with post-like features at all four corners 2206-2209. Alternate SPIM-plate shapes may be employed. For example, Figure 22B shows a hexagonal movable plate 2210 cut from the middle layer (2163 in Figure 21D) within a pattern of three triangular post-like features 2212-2214.

Figures 23A-B illustrate operation of a SPIM within a SPIM-based reflective tag or label. In Figure 23A, the SPIM 2302 is in a fully reflective state in which the movable plate 2304 is positioned up against the fixed plate 2306. In Figure
23B, the movable plate 2304 has been pulled downward by electronic features in the control plate 2308 to produce a cavity of depth δ 2310. As discussed in preceding subsections, the depth of the cavity determines the wavelength or wavelength of light reflected by the SPIM. Figures 23A-B show a single SPIM, but, as discussed above, the SPIMs are arranged in two-dimensional arrays to create reflective display elements, such as digit displays, character displays, symbol displays, and period or point displays. In these arrays, the fixed plate 2306 is a small portion of the top layer (2162 in Figure 21D), the movable plate 2304 is cut from the middle layer (2163 in Figure 21D), and the control plate 2308 is a small region of the base or lowest layer (2164 in Figure 21D).

Figures 24-28B illustrate an example process for manufacturing a SPIM-based reflective tag or label. Figure 24 illustrates preparation of the top, transparent, semi-reflective layer (2163 in Figure 21D). In certain implementations, this top layer, and the reflective label or reflective tag that includes the layer, are rigid or semi-rigid. In these cases, the top layer may be based on a substrate 2402 made of glass, a rigid polymer, such as polycarbonate, thin ceramic layers, or other such rigid materials. In alternative implementations, the reflective tag or label is flexible, and all three layers 2162-2164 in Figure 21D are therefore based on flexible materials. These may include polyvinyl chloride sheets, polyethylene sheets, polyimide sheets, and thin polyethylene terephthalate sheets. In a first step, the top-layer substrate 2402 is coated with a thin reflective layer 2404. This thin reflective layer may be prepared by room-temperature sputtering or other vapor-deposition and vacuum-coating techniques. The reflective layer is generally a metal, such as silver, aluminum, chromium, molybdenum, tungsten, tin, iron, or various alloys of these and other metals. In a second step, the reflective layer is additionally coated with a protective hydrophobic-film layer 2406, which facilitates elimination of static interactions between the adjacent surfaces of the transparent fixed plate and movable plate of the SPIMs and provides a barrier to prevent metal oxidation. The hydrophobic-film layer may be composed of silicon dioxide, a silicon nitride, or other protective and hydrophobic layer-forming compounds. The protective and hydrophobic film layer 2406 can be applied to the reflective layer by atomic-layer-deposition and self-
assembled-monolayer techniques, in various fabrication-process implementations and may, in certain cases, constitute a self-assembled monolayer ("SAM").

Figure 25 illustrates addition of the doubly reflective middle layer (2163 in Figure 21D) to the top semi-reflective layer. In Figure 25, the top semi-reflective layer (2162 in Figure 21D) is shown as a lower layer 2502 that includes the above-described protective and hydrophobic film 2406, reflective metal layer 2404, and substrate 2402. The middle layer (2163 in Figure 21D) 2504 includes a doubly reflective layer 2506 to which a protective and hydrophobic film layer 2508 is applied in a fashion similar to application of the protective and hydrophobic film layer 2406 to the reflective layer 2404 of the top layer 2502. The doubly reflective layer 2506 includes a middle polymer layer, such as a polyethylene terephthalate layer 2510 that is coated on each side with aluminum 2512 or another reflective metal. In certain implementations, post-like features (2202 in Figure 22A) are applied to one of the two hydrophobic and protective films 2406 and 2508 prior to application of the middle layer 2504 to the top layer 2502. In these implementations, the post-like features may be applied by ink-jet or dot-matrix printing techniques, by stamping, or by other application methods and may be composed of nano-imprint-lithography glue or ultra-violet glue. In other implementations, described below, the posts are created by laser welding. The laser welding can form posts either from portions of the adjacent surfaces of the top and middle layers 2502 and 2504 or may use, in addition, an applied material, such as a glue. Please note that the illustrated thicknesses of individual layers and coating do not necessarily reflect the actual widths and relative widths of the layers and coatings in actual reflective-label implementations.

The top layer 2502 and the middle layer 2504 are generally pressed firmly together between rollers or other suitable mechanical devices. The protective and hydrophobic films of the adjacent features of the top and middle layers, 2406 and 2508, need to be firmly pressed together in order to eliminate bubbles and any type of fold, ripple, or other departure from planarity. In certain implementations of the manufacturing process, the two layers may be joined together under vacuum conditions, in a dust-free environment, in order to eliminate bubbles and surface contaminants that may lead to irregularities and departures from planarity in the adjacent protective and hydrophobic surfaces.
Figures 26A-28B illustrate one of a variety of different possible manufacturing-process implementations that begin with the compressed-together top and middle layers, as illustrated in Figure 25, and produce a three-layer reflective tag or label, as illustrated in Figure 21D. Figure 26A shows the compressed-together top and middle layers. The top layer 2602 underlies the middle layer 2604. Cross-hatching is used to illustrate the reflective layer of the middle layer 2606 that is not adjacent to the top layer 2602. As shown in Figure 26B, a next layer 2610 is applied to reflective surface 2606 of the middle layer. The next layer may be a layer of fine plastic or composite particles or may be a photo-resist-like layer. This next layer is applied in order to generate post-like features between the middle layer and the bottom layer (2164 in Figure 21D) on which logic circuits and other driving features are imprinted or stamped.

Figures 27A-B illustrate a two-step process that creates the post-like features within the SPIM-based reflective label or tag. The two steps are carried out using laser-writing or laser-welding techniques. In a first step, shown in Figure 27A, precisely targeted laser light, represented in Figure 27A by vertical arrows, such as vertical arrow 2702, is applied to the top layer 2602 to a depth that includes at least the first metal layer (2512 in Figure 25) of the middle layer 2604 to produce, by laser welding, post-like features 2704-2709 within the top and middle layers. These post-like features bond the top and middle layers together at discrete grid points. In a second step, shown in Figure 27B, focused and precisely targeted laser light, represented by vertical arrows, such as vertical arrow 2710, are applied to the next layer 2610 in order to create, by melting or other laser-light-heating processes, continuations of the post-like features 2712-2717 within the next layer 2610 above the cross-hatching-denoted reflective layer of the middle layer 2604. The two steps illustrated in Figures 27A-B may be carried out in a single-alignment process step in which the upward-directed and downward-directed laser light is produced by mechanically aligned laser arrays.

Figures 28A-B illustrate final steps of the manufacturing process for SPIM-based reflective labels and tags illustrated in Figures 24-28B. As shown in Figure 28A, laser-cutting techniques are used to cut the middle layer to form the movable plates of the SPIMs. In Figure 28A, the results of laser cutting are shown as
a grid-like pattern of cuts or divisions, such as division 2802, within the middle layer 2604. Then, in a second process, the portion of the next layer (2610 in Figure 26B) not incorporated into the post-like-feature extensions 2712-2717 in Figure 27B is removed by any of various different layer-removal processes. When the next layer is a layer of fine plastic particles, the layer may be removed using an air stream or fluid stream. When the next layer is a photo-resist-like material, various type of photo resist-removal processes, including etching processes, may be employed. Finally, as illustrated in Figure 28B, the bottom layer 2804 (2164 in Figure 21D) is aligned with the patterned movable plates on the surface of the middle layer 2604 and bonded to the post-like-feature extensions. The bottom layer 2804 may be a flexible printed circuit or other type of substrate onto which logic circuits and signal lines are imprinted, stamped, or formed by other electronics-forming processes. Bonding of the bottom layer 2804 to the post-like-feature extensions may be obtained by an additional step of laser heating, using glues, by compression, or by other methods.

Figures 29A-J illustrate an alternative manufacturing process for SPIM-based reflective labels and tags. In Figures 29A-J, the sublayers within the doubly reflective middle layer (2504 in Figure 25) and the top semi-reflective layer (2502 in Figure 25) are not shown, for simplicity and clarity of illustration.

Figure 29A shows a first step in the alternative manufacturing process. The doubly reflective middle-layer film 2902 is patterned to produce small apertures at the grid points of a rectangular, hexagonal, or other type of grid that defines the post locations and vertices of the movable plates of the SPIMs of an array of SPIMs. In Figure 29A, the patterned middle-layer film 2904 shows 21 apertures, including aperture 2906. Of course, in an actual middle-layer film, there may be thousands, tens of thousands, or hundreds of thousands, or more, apertures. The apertures may be created by laser ablation or laser writing, mask photolithography, mechanical stamping, or by thermo-mechanical-impression technology.

Next, as shown in Figures 29B-D, the patterned middle-layer film is bonded to the top semi-reflective layer. Figure 29B shows the patterned middle-layer film 2904 above the top-layer film 2908. As shown in Figure 29C, a line of adhesive 2910 has been deposited on the top-layer film 2908 along the edges, or borders, of the top-level film. In at least one place 2912, the line of adhesive is discontinuous so that
a port is obtained to interconnect what will be an inner chamber between the top-layer film and the middle-layer film with the external environment. In the case of large top-layer and middle-layer films, the adhesive may be applied to the top layer in various window-pane-like or grid-like patterns in order to provide proper support across the entire areas of the top-layer and middle-layer films and produce multiple internal, interconnected chambers. As shown in Figure 29D, the lines of adhesive have been applied to the top-layer film, or, in alternative processes, to the middle-layer film, and the two films are bonded together 2914 to produce a ported, internal chamber that will include the movable plates and top semi-reflective layer of an array of SPIMs.

In a next step, shown in Figure 29E, a thin layer of UV adhesive 2916 is applied to the side of the patterned middle-layer film 2904 opposite from the internal chamber formed between the middle-layer film and the top-layer film 2908 by the applied lines of adhesive 2910. Next, as shown in Figure 29F, a vacuum is applied to the internal chamber or chambers between the top-layer and middle-layer films, via one or more ports 2912, to evacuate the internal chamber or chambers between the top-layer and middle-layer films, indicated in Figure 29F by arrow 2920 indicating vacuum-induced flow of air out from the internal chamber or chambers. By applying the vacuum, the liquid UV adhesive 2916 is drawn downward, through the apertures patterned into the middle-layer film, to form nascent posts, as shown in Figure 29G. In Figure 29G, the area of the various layers in proximity to one of the middle-layer apertures is shown, UV adhesive is shown to have been drawn down, through the aperture 2922 in the middle-layer film 2904 to form a nascent post, or liquid plug 2924, that extends downward from the patterned middle-layer film 2904 to the top-layer film 2908. The applied vacuum, or suction force, is calibrated to draw only a sufficient amount of UV adhesive through the pattern apertures to create nascent posts, or plugs, corresponding to a cylindrical footprint below the aperture extending down to the top-layer film. In alternative processes, rather than applying a vacuum through ports left in the adhesive lines, a force may be applied downward on the layer of UV adhesive 2916 to force the UV adhesive down through the apertures in the middle layer to form the nascent posts or liquid plugs. Following formation of the nascent posts, UV radiation, represented in Figure 29G by upward-pointing
arrows 2930-2932, is transmitted through the semi-reflective top layer 2908 into the nascent posts in order to fix or cure the UV adhesive within a cylindrical volume that extends perpendicular to the top and middle layers through the apertures of the grid-like pattern of apertures in the middle layer. The UV radiation is applied for a sufficient time to fix or cure the UV adhesive within the cylindrical nascent posts, without fixing or curing the remaining UV adhesive within the layer of UV adhesive 2916 lying above the patterned, middle-layer film. Formation of the posts that anchor the three layers is therefore carried out without costly and time-intensive alignment steps.

Next, as shown in Figure 29H, the unfixed and uncured UV adhesive lying above the middle-layer film is removed. Removal of the uncured UV adhesive leaves a fully formed post 2936 that extends from a position well above the surface of the middle-layer film downward, through the aperture in the middle-layer film 2904 and through the internal chamber between the middle-layer film 2904 and the top-layer film 2908, to the surface of the top-layer film. Figure 291 illustrates the posts extending above the surface of the middle-layer film through the pattern of apertures. In addition, the portions of four of the posts within the internal chamber 2940-2943 are shown in dashed lines to indicate one nascent SPIM within a nascent array of SPIMs. In a next step, as indicated in Figure 291 by a grid-like pattern of lines, including line 2946, the middle-layer is cut, using laser ablation or laser writing, to form the movable plates for each SPIM in the array of SPIMs. The posts may be used for alignment during the laser-ablation or laser-writing step. Note that, as in the previously discussed methods, the movable plates remain fixed, at their vertices, to the posts. Note also that, in the current illustrations, the thickness of the layers is significantly exaggerated with respect to the lateral SPIM dimensions. In certain implementations, the posts extending above the middle layer may be planarized by any of various different planarization techniques, including laser-based techniques.

In alternative implementations, because of the thickness of the layer of applied UV adhesive (2916 in Figure 29F) is strictly controlled, planarization is not needed. Finally, as shown in Figure 29J, the driver layer 2950 is aligned with, and bonded to, the tops of the posts extending upward from the middle-layer film. This completes fabrication of the array of SPIMs. In certain implementations, additional adhesive
lines, similar to the adhesive lines (2910 in Figure 29C) used to create the inner chamber between the top-layer 2908 and middle layer 2904, may be additionally employed for uniformity of support and environmental integrity between the driver layer 2950 and the middle layer 2904.

Many additional alternative manufacturing processes may be employed in order to manufacture the above-described three-layer SPIM-based reflective tag or label. Any of many different types of polymers, glasses, ceramic materials, and composite materials may be used for the base or substrate portions of the three layers 2162-2164 in Figure 21D. The reflective layers can be prepared from any of many different reflective metals and metal alloys by various coating and layering techniques. Post-like-feature generation can be carried out as described above by various different types of nano-imprint lithography, ink-jet and laser-jet material deposition, and various types of laser-mediated processes. The electronic components that drive the SPIMs, receive input data from connectors or RF modules, and receive power from a power supply and may be deposited on the surface of the bottom layer (2164 in Figure 21D) by any of many different circuit-fabrication processes, including the well-known circuit-printing processes used to produce flexible printed circuits. Between the various steps described above, laser ablation and other laser-mediated processes may be employed to planarize intermediate surfaces in preparation for bonding. In certain implementations, tiny apertures are bored into the movable plates of the SPIMs to facilitate rapid motion and control of the cavity depth. SPIM dimensions may range from one or more millimeters down to tens or hundreds of micrometers.

Although the present disclosure has been described in terms of particular implementations, it is not intended that the disclosure be limited to these implementations. Modifications within the spirit of the disclosure will be apparent to those skilled in the art. For example, additional layers or sub-layers may be employed, in alternative implementations. Labels of many different sizes and thicknesses may be produced by varying the thicknesses of substrates and applied coatings and by varying the dimensions of the substrate layers or by stamping or cutting reflective labels from large array-like sheets of reflective labels.
It is appreciated that the previous description of the disclosed implementations is provided to enable any person skilled in the art to make or use the present disclosure. Various modifications to these implementations will 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 the disclosure. Thus, the present disclosure is not intended to be limited to the implementations shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.
CLAIMS

1. A reflective label comprising:
   a first layer composed of a reflective coating applied to a first-layer substrate;
   a second composed of reflective coatings on both sides of a second-layer substrate, the middle layer cut into moveable self-parallelizing-interferometric-modulator moveable plates which move relative to the first layer;
   a third layer composed of a third-layer substrate, on one surface imprinted or layered with electronic signal lines and logic circuitry; and
   an external access feature.

2. The reflective label of claim 1 further including a power source selected from among:
   a connector that connects the reflective label to an external power source;
   a non-rechargeable battery; and
   a rechargeable battery connected to one of an external connector, a photovoltaic cell, and a radio-frequency identifier tag.

3. The reflective label of claim 1 wherein the first-layer substrate, the second-layer substrate, and the third-layer substrate are each one of:
   rigid;
   semi-rigid; and
   flexible.

4. The reflective label of claim 1 wherein the first-layer substrate, the second-layer substrate, and the third-layer substrate are each one of:
   a polymer sheet;
   a glass sheet;
   a ceramic sheet; and
   a composite sheet.
5. The reflective label of claim 1 wherein the first-layer substrate, the second-
layer substrate, and the third-layer substrate are composed of one of:
   ethylene terephthalate;
   polycarbonate;
   polyvinyl chloride, and
   polyethylene.

6. The reflective label of claim 1 wherein the first-layer comprises:
   the first-layer substrate;
   a reflective layer deposited onto one side of the first-layer substrate; and
   a protective and hydrophobic layer deposited onto the reflective layer.

7. The reflective label of claim 6 wherein the reflective layer is a metal layer.

8. The reflective label of claim 7 wherein the reflective layer is deposited onto
   the first-layer substrate by one of:
   vacuum-coating; and
   vapor-deposition.

9. The reflective label of claim 7 wherein the reflective layer is a metal or metal
   alloy, the metal or metals selected from among:
   silver;
   aluminum;
   chromium;
   molybdenum;
   tungsten;
   tin; and
   iron, or various alloys of these and other metals.

10. The reflective label of claim 6 wherein the protective and hydrophobic layer is
    formed by one of:
    atomic-layer-deposition; and
a self-assembled-monolayer method.

11. The reflective label of claim 6 wherein the protective and hydrophobic layer is composed of one of:
    silicon dioxide; and
    silicon nitride.

12. The reflective label of claim 1 wherein the second-layer comprises:
    the second-layer substrate;
    a first reflective layer deposited onto a first side of the first-layer substrate;
    a second reflective layer deposited onto a second side of the first-layer substrate; and
    a protective and hydrophobic layer deposited onto the first reflective layer.

13. The reflective label of claim 12 wherein the first and second reflective layers are metal layers.

14. The reflective label of claim 13 wherein the first and second reflective layers are deposited onto the first-layer substrate by one of:
    vacuum-coating; and
    vapor-deposition.

15. The reflective label of claim 13 wherein the first and second reflective layers are a metal or metal alloy, the metal or metals selected from among:
    silver;
    aluminum;
    chromium;
    molybdenum;
    tungsten;
    tin; and
    iron, or various alloys of these and other metals.
16. The reflective label of claim 12 wherein the protective and hydrophobic layer is formed by one of:
   atomic-layer-deposition; and
   a self-assembled-monolayer method.

17. The reflective label of claim 12 wherein the protective and hydrophobic layer is composed of one of:
   silicon dioxide; and
   silicon nitride.

18. The reflective label of claim 1 wherein the third layer is a flexible printed circuit.

19. The reflective label of claim 1 further including post-like features a points of a grid that define the self-parallelizing-interferometric-modulators of self-parallelizing-interferometric-modulator arrays that implement display elements.

20. The reflective label of claim 19 wherein each post-like feature bond the first layer to the second layer and additionally separated the second layer from the third layer and bonds the second layer to the third layer.

21. The reflective label of claim 19 wherein the post-like features are fabricated by laser illumination of the grid points, the laser illumination resulting in one or more of:
   laser welding of layers or coatings; and
   curing or melting of applied post-like-feature material.
FIG. 2
FIG. 3

\[ H = \text{angle from red} \]

\[ S = \frac{d' \cdot d}{d} \]

\[ L = \perp \text{to black} \]
FIG. 4
FIG. 5
16/42

\[(\lambda, P_y, P_w, P_z) \text{ or } (P_b, P_r, P_w, P_z)\]

..  0
..  1
..  2
..  3
..  4
..  5

\[011010101011111110000000000000\]

..  n-3
..  n-2
..  n-1
..  n

FIG. 14
FIG. 15A
Wavelength ($\lambda$)

<table>
<thead>
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<tbody>
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<td>..</td>
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Blue ratio ($f$)

<table>
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<th>241</th>
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FIG. 16

Prepare color look-up table

Receive an indication of an RGB color model

Allocate and initialize a look-up table with \( x \) entries

for \( i = 0 \) to \( x \)

Extract \( r, g, b \) values from \( i \)

Convert \( (r, g, b) \) to \( (h, s, l) \)

Calculate percentages: \( P_s, P_w, \) and \( P_t \)

Hue in \([0, 240]\)?

\( i = i + 1 \)

Extract wavelength \( \lambda \) from wavelength-hue look-up table
when \( P_s \neq 0 \);
Set \( \lambda = 0 \) when \( P_s = 0 \)

Package \( \lambda, P_s, P_w, \) and \( P_t \) into a 32-bit integer \( t \), and store \( t \) at table entry with index \( i \)

Extract blue ratio from ratio-hue look-up table

Calculation percentages: \( P_b, P_r, \) and \( P_t \)

Package \( P_b, P_r, P_w, \) and \( P_t \) into a 32-bit integer \( t \), and store \( t \) at table entry with index \( i \)

\( i = x \)?
FIG. 17
Image Signal

Pixel (1,1)
($\lambda^{11}, P_z^{11}, P_w^{11}, P_k^{11}$)

m x n array

Pixel (i,j)
($\lambda^{ij}, P_z^{ij}, P_w^{ij}, P_k^{ij}$)

Pixel (m,n)
($P_b^{mn}, P_r^{mn}, P_w^{mn}, P_k^{mn}$)

FIG. 18
FIG. 20

Image signal processing and display

Receive image signal

Initial transformation to RGB format

Transform RGB to new color model

Map color coordinates to each pixel

Voltage generator/control unit obtains voltage data from table

Voltage generator applies voltage data to row/column drivers

For each row of pixels

Row driver activates the selected row

Column driver applies data voltages to pixels on the current row

Row driver de-activates the current row

Row driver moves to the next row

Return to the first row in the pixel matrix

Frame period elapsed?

More rows?

Finish

Y

N
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
G09F 9/30(2006.01)i, G09F 9/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G09F 9/30; G02B 26/08; G02B 26/00; H05K 3/10; B81B 3/00; G02F 1/01; G02F 1/19; G09G 5/00; G09F 9/00

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: reflective label, reflective coating, self-parallelizing interferometric modulator, moveable

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents:
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"&" document member of the same patent family

Date of the actual completion of the international search
27 January 2016 (27.01.2016)

Date of mailing of the international search report
27 January 2016 (27.01.2016)

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
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