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(71) **Applicant** *(for all designated States except US)*: **E INK CORPORATION** [US/US]; 733 Concord Avenue, Cambridge, Massachusetts 02138-1002 (US).

(72) **Inventors; and**

(75) **Inventors/Applicants** *(for US only)*: **PAOLINI, JR., Richard J.** [US/US]; 10 Hickory Hill Lane, Framingham, Massachusetts 01702 (US). **TELFER, Stephen J.** [US/US]; 40 College Avenue, Arlington, Massachusetts 02474-2254 (US). **BOUCHARD, Alain** [US/US]; Unit 8, 944 Dorchester Avenue, Dorchester, Massachusetts 02125 (US). **ATKINSON, John** [US/US]; Apartment No. 1, 7 Farragut Avenue, Somerville, Massachusetts 02144 (US).

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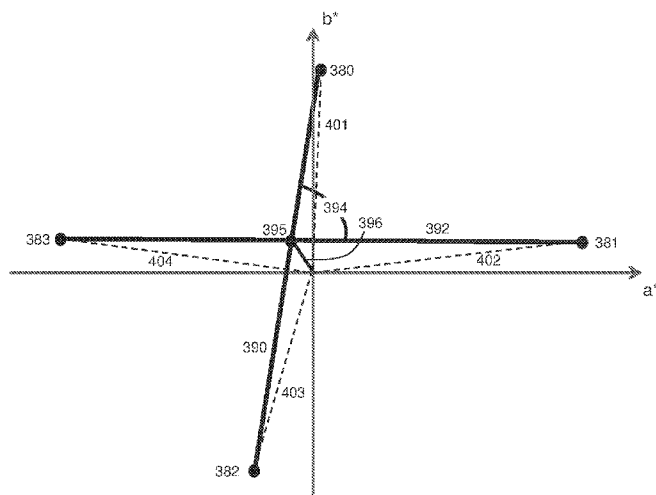(54) **Title**: TETRACHROMATIC COLOR FILTER ARRAY

FIG. 3B

(57) **Abstract**: A tetrachromatic color filter array comprises multiple pixels, each of which comprises first, second, third and fourth sub-pixels having first, second, third and fourth hues, P1, P2, P3 and P4 respectively, these first, second, third and fourth hues having first, second and third hue angles, $h1$, $h2$, $h3$ and $h4$ respectively. The hues of the sub-pixels such that $h3$ equals $h1 + (180° \pm 10°)$ and $h4$ equals $h2 + (180° \pm 10°)$ in the a*b* plane of the La*b* color space.

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TETRACHROMATIC COLOR FILTER ARRAY

[0001]   This invention relates to electro-optic displays and color filters for use in such displays.

[0002]   The background nomenclature and state of the art regarding electro-optic displays is discussed at length in U.S. Patent No. 7,012,600 to which the reader is referred for further information. Accordingly, this nomenclature and state of the art will be briefly summarized below.

[0003]   The term "electro-optic", as applied to a material or a display, is used herein in its conventional meaning in the imaging art to refer to a material having first and second display states differing in at least one optical property, the material being changed from its first to its second display state by application of an electric field to the material. Although the optical property is typically color perceptible to the human eye, it may be another optical property, such as optical transmission, reflectance, luminescence or, in the case of displays intended for machine reading, pseudo-color in the sense of a change in reflectance of electromagnetic wavelengths outside the visible range.

[0004]   The terms "bistable" and "bistability" are used herein in their conventional meaning in the art to refer to displays comprising display elements having first and second display states differing in at least one optical property, and such that after any given element has been driven, by means of an addressing pulse of finite duration, to assume either its first or second display state, after the addressing pulse has terminated, that state will persist for at least several times, for example at least four times, the minimum duration of the addressing pulse required to change the state of the display element.

[0005]   Several types of electro-optic displays are known, for example:

(a)   rotating bichromal member displays (see, for example, U.S. Patents Nos. 5,808,783; 5,777,782; 5,760,761; 6,054,071 6,055,091; 6,097,531; 6,128,124; 6,137,467; and 6,147,791);

(b)   electrochromic displays (see, for example, O'Regan, B., et al., Nature 1991, *353*, 737; Wood, D., Information Display, *18(3)*, 24 (March 2002); Bach, U., et al., Adv. Mater., 2002, *14(11)*, 845; and U.S. Patents Nos. 6,301,038; 6,870.657; and 6,950,220);

(c)   electro-wetting displays (see Hayes, R.A., et al., "Video-Speed Electronic Paper Based on Electrowetting", Nature, *425*, 383-385 (25 September 2003) and U.S. Patent Publication No. 2005/0151709);

(d)   particle-based electrophoretic displays, in which a plurality of charged particles move through a fluid under the influence of an electric field (see U.S. Patents Nos. 5,930,026; 5,961,804; 6,017,584; 6,067,185; 6,118,426; 6,120,588; 6,120,839; 6,124,851; 6,130,773; and 6,130,774; U.S. Patent Applications Publication Nos. 2002/0060321; 2002/0090980; 2003/0011560; 2003/0102858; 2003/0151702; 2003/0222315; 2004/0014265; 2004/0075634; 2004/0094422; 2004/0105036; 2005/0062714; and 2005/0270261; and International Applications Publication Nos. WO 00/38000; WO 00/36560; WO 00/67110; and WO 01/07961; and European Patents Nos. 1,099,207 B1; and 1,145,072 B1; and the other MIT and E Ink patents and applications discussed in the aforementioned U.S. Patent No. 7,012,600).

[0006]   There are several different variants of electrophoretic media. Electrophoretic media can use liquid or gaseous fluids; for gaseous fluids see, for example, Kitamura, T., et al., "Electrical toner movement for electronic paper-like display", IDW Japan, 2001, Paper HCS1-1, and Yamaguchi, Y., et al., "Toner display using insulative particles charged triboelectrically", IDW Japan, 2001, Paper AMD4-4); U.S. Patent Publication No. 2005/0001810; European Patent Applications 1,462,847; 1,482,354; 1,484,635; 1,500,971; 1,501,194; 1,536,271; 1,542,067; 1,577,702; 1,577,703; and 1,598,694; and International Applications WO 2004/090626; WO 2004/079442; and WO 2004/001498. The media may be encapsulated, comprising numerous small capsules, each of which itself comprises an internal phase containing electrophoretically-mobile particles suspended in a liquid suspending medium, and a capsule wall surrounding the internal phase. Typically, the capsules are themselves held within a polymeric binder to form a coherent layer positioned between two electrodes; see the aforementioned MIT and E Ink patents and applications. Alternatively, the walls surrounding the discrete microcapsules in an encapsulated electrophoretic medium may be replaced by a continuous phase, thus producing a so-called polymer-dispersed electrophoretic display, in which the electrophoretic medium comprises a plurality of discrete droplets of an electrophoretic fluid and a continuous phase of a polymeric material; see for example, U.S. Patent No. 6,866,760. For purposes of the present application, such polymer-dispersed electrophoretic media are regarded as sub-species of encapsulated electrophoretic

media. Another variant is a so-called "microcell electrophoretic display" in which the charged particles and the fluid are retained within a plurality of cavities formed within a carrier medium, typically a polymeric film; see, for example, U.S. Patents Nos. 6,672,921 and 6,788,449.

[0007]   Although electrophoretic media are often opaque (since, for example, in many electrophoretic media, the particles substantially block transmission of visible light through the display) and operate in a reflective mode, many electrophoretic displays can be made to operate in a so-called "shutter mode" in which one display state is substantially opaque and one is light-transmissive. See, for example, U.S. Patents Nos. 5,872,552; 6,130,774; 6,144,361; 6,172,798; 6,271,823; 6,225,971; and 6,184,856. Dielectrophoretic displays, which are similar to electrophoretic displays but rely upon variations in electric field strength, can operate in a similar mode; see U.S. Patent No. 4,418,346. Other types of electro-optic displays may also be capable of operating in shutter mode. Electro-optic media operating in shutter mode may be useful in multi-layer structures for full color displays; in such structures, at least one layer adjacent the viewing surface of the display operates in shutter mode to expose or conceal a second layer more distant from the viewing surface.

[0008]   An encapsulated electrophoretic display typically does not suffer from the clustering and settling failure mode of traditional electrophoretic devices and provides further advantages, such as the ability to print or coat the display on a wide variety of flexible and rigid substrates. (Use of the word "printing" is intended to include all forms of printing and coating, including, but without limitation: pre-metered coatings such as patch die coating, slot or extrusion coating, slide or cascade coating, curtain coating; roll coating such as knife over roll coating, forward and reverse roll coating; gravure coating; dip coating; spray coating; meniscus coating; spin coating; brush coating; air knife coating; silk screen printing processes; electrostatic printing processes; thermal printing processes; ink jet printing processes; electrophoretic deposition (See U.S. Patent No. 7,339,715); and other similar techniques.) Thus, the resulting display can be flexible. Further, because the display medium can be printed (using a variety of methods), the display itself can be made inexpensively.

[0009]   Other types of electro-optic media may also be used in the displays of the present invention.

[0010]   Many types of electro-optic media are essentially monochrome, in the sense that any given medium has two extreme optical states and a range of gray levels lying between the two extreme optical states. As already indicated, the two extreme optical states need not be black and white. For example, one extreme optical state can be white and the other dark blue, so that the intermediate gray levels will be varying shades of blue, or one extreme optical state can be red and the other blue, so that the intermediate gray levels will be varying shades of purple.

[0011]   There is today an increasing demand for full color displays, even for small, portable displays; for example, most displays on cellular telephones are today full color. To provide a full color display using monochrome media, it is either necessary to place a color filter array where the display can be viewed through the color filter array, or to place areas of different electro-optic media capable of displaying different colors adjacent one another.

[0012]   Figure 1 of the accompanying drawings includes an exemplary schematic section through a color electrophoretic display (generally designated 100) comprising a backplane 102. To this backplane 102 has been laminated an inverted front plane laminate as described in the aforementioned United States Patent No. 6,982,178. The front plane laminate can be formed by coating capsules on a conductive layer (usually indium tin oxide (ITO)) formed on film 104 (e.g., a polyethylene terephthalate film) to form a monochrome electrophoretic medium layer 106 having black and white extreme optical states. In addition, an adhesive layer can be separately coated on a release sheet (not shown) and adhered to the capsule layer to form adhesive layer 108. The release sheet can be removed, and the front plane laminate can be laminated to backplane 102. A color filter array 110 having red, green and blue areas can be separately printed or otherwise formed on substrate 112 (e.g., a glass substrate). The color filter array and substrate can then be adhered to film 104, for example, by depositing adhesive layer 114 on color filter array 110 or film 106.

[0013]   In the display 100, the electrophoretic layer 106 is of course not 100 percent reflective, and the saturation of the color filter elements in the array 110 must be reduced to allow enough light to pass through the array 110, reflect from the electrophoretic layer 106, and return through the array 110. However, using a color filter array does enable a single black/white electro-optic medium to provide a full color display, and it is typically easier to control the color gamut of a display by

varying the colors in a color filter array than by varying the colors of electro-optic media, there being far more materials available for use in color filter arrays than in most electro-optic media.

[0014]   The color filter array shown in Figure 1 is an RGB color filter. It is known that improved contrast can be obtained from a filter if a white pixel is included, thus producing an RGBW filter. Figures 2 of the accompanying drawings includes an exemplary illustration of a display (generally designated 200) including one such filter arrangement. In Figure 2, the electrophoretic medium layer, having extreme black and white optical states, is illustrated as layer 206. The color filter array 210 includes red 212, blue 214, green 216, and white 218 areas aligned with pixel electrodes (not shown). Inset 220 includes a top-side view of region 222 within display 200, which illustrates the layout of a red, blue, green, and white region within a pixel.

[0015]   Although improvements have been achieved with RGBW color filters, it has been found that when an RGBW filter is used with an electro-optic display and the red, green and blue pixels use reasonably saturated red, green and blue colors, the white state of the display is rather poor. It has been suggested that a CMY (cyan/magenta/yellow) filter, similar to the CMY printing systems used in the color printing industry, be used in place of the RGB filter. In color printing, the cyan, magenta and yellow inks can overlap, so the resultant print can provide well saturated colors using a subtractive color mode. No such overlap is possible in a color filter used with an electro-optic display, because the cyan, magenta and yellow pixels lie alongside each other and do not overlap. It has been found that using a CMYW (cyan/magenta/yellow/white) color filter in place of an RGBW color filter improves the white state of the display but causes red, green and blue colors to look desaturated, i.e., "washed out".

[0016]   Accordingly, there is a need for improved color filter arrays in electro-optic displays, and this invention seeks to provide such improved color filter arrays, and displays containing such color filters.

[0017]   It has now been found that the appearance of color images on electro-optic displays can be improved by using a new set of four primary colors. The result of using the new set of four primary colors is a compromise between the aforementioned properties of RGB and CMY primaries; more specifically, the new set of four primaries produces red, green and blue color saturation greater than that

achieved by CMY primaries, while producing a white state better than that achieved with RGB primaries. The resulting properties render color images more attractive to the human eye than those achieved with either RGB or CMY primaries. In one set of embodiments, the four primary colors can be selected as a set of two pairs of hues, P1/P3 and P2/P4. Hue pair P1/P3 and/or hue pair P2/P4 can be selected such that they average to gray.

[0018]   Accordingly, in one aspect, a color filter array comprising four colors is provided. In some embodiments, the color filter array comprises a plurality of pixels, comprising: a first sub-pixel having a first hue P1 positioned at a first hue angle $h1$ in the a*b* plane of the La*b* color space; a second sub-pixel having a second hue P2 positioned at a second hue angle $h2$ in said a*b* plane; a third sub-pixel having a third hue P3 positioned at a third hue angle $h3$ equal to $h1 + (180° ± 10°)$ (i.e., $h1 + 170°$ to $h1 + 190°$) in said a*b* plane; and a fourth sub-pixel having a fourth hue P4 positioned at a fourth hue angle $h4$ equal to $h2 + (180° ± 10°)$ in said a*b* plane.

[0019]   In some embodiments, the hue pairs can include complementary subtractive/additive color pairs. For example, hue pair P1/P3 and/or hue pair P2/P4 can be selected from, in some cases, red/cyan (R/C), green/magenta (G/M) and/or blue/yellow (B/Y). In some embodiments, hue pairs P1/P3 and P2/P4 can be selected such that one is R/C and the other is G/M; such that one is R/C and the other is B/Y; or such that one is G/M and the other is B/Y.

[0020]   The line connecting hue P1 to hue P3 and the line connecting hue P2 to hue P4 (as defined in the preceding paragraphs) can meet at an angle close to a right angle, in some embodiments. For example, in some embodiments, a first line connecting hue P1 to hue P3 and a second line connecting hue P2 to hue P4 can intersect within the a*b* plane of the La*b* color space such that they define angles of not less than about 70°.

[0021]   Optionally, the line connecting hue P1 to P3 and the line connecting hue P2 to hue P4 can intersect near the origin of the a*b* plane of the La*b* color space. In some embodiments, the distance from the origin of the a*b* plane to the intersection of the lines connecting hue P1 to P3 and hue P2 to hue P4 can be less than about 20% of the shortest of the distances between the origin of the a*b* plane and any of hues P1, P2, P3, and P4.

[0022]   In one set of embodiments, the color filter array comprises a plurality of pixels, comprising: a first sub-pixel having a first hue P1 positioned at a first hue angle *h1* in the a*b* plane of the La*b* color space; a second sub-pixel having a second hue P2 positioned at a second hue angle *h2* in said a*b* plane; a third sub-pixel having a third hue P3 positioned at a third hue angle *h3* equal to *h1* + (180° ± 10°) in said a*b* plane; and a fourth sub-pixel having a fourth hue P4 positioned at a fourth hue angle *h4* equal to *h2* + (180° ± 10°) in said a*b* plane, wherein the angle between hue angle h1 and hue angle h2 in said a*b* plane is from about 70° to about 110°.

[0023]   In some embodiments, the hue of each sub-pixel in the color filter array has a C* value greater than 5 ΔE units from the origin (where C* has the conventional meaning of $[(a*)^2 + (b*)^2]^{0.5}$, i.e., it represents the distance from the origin of the a*b* plane).

[0024]   Also described are electro-optic displays provided with the color filters described herein. This embodiments described herein can be used in such displays having an electro-optic medium which is reflective, such that light passes through the color filter, is reflected from the electro-optic medium, and passes back through the color filter to an observer. The electro-optic display may make use of any of the types of electro-optic medium discussed above. Thus, the electro-optic material may comprise a rotating bichromal member or electrochromic material. Alternatively, the electro-optic material may comprise an electrophoretic material comprising a plurality of electrically charged particles disposed in a fluid and capable of moving through the fluid under the influence of an electric field. The electrically charged particles and the fluid may be confined with a plurality of capsules or microcells. Alternatively, the electrically charged particles and the fluid may be present as a plurality of discrete droplets surrounded by a continuous phase comprising a polymeric material. The fluid may be liquid or gaseous.

[0025]   The embodiments described herein can be used as part of an electronic book reader, portable computer, tablet computer, cellular telephone, smart card, sign, watch, shelf label, and/or flash drive comprising a display.

[0026]   In some embodiments, it is desirable to convert RGB image data for use with the inventive color filters described herein. Accordingly, a method of converting an RGB image for display on the inventive displays described herein is provided.

[0027]   As already mentioned, Figure 1 of the accompanying drawings comprises an exemplary schematic section through a color electrophoretic display.

[0028]   As already mentioned, Figure 2 of the accompanying drawings comprises an exemplary schematic section through a color electrophoretic display comprising an RGBW color filter.

[0029]   Figures 3A-3B comprises exemplary plots of the a*b* plane in the La*b* color space, including exemplary hues that can be used in association with some of the embodiments described herein.

[0030]   Figures 4A-4D comprise exemplary spectra of hues that can be used in some of the embodiments described herein.

[0031]   Figures 5A-5D comprise (A) an exemplary projection of the color gamut in the a*b* plane for a color filter array with the spectra illustrated in Figures 4A-4D, (B) an exemplary plot of color saturation plotted against the lightness of that color for a color filter array with the spectra illustrated in Figures 4A-4D, (C) an exemplary projection of the color gamut in the a*b* plane for an idealized RGBW color filter array, and (D) an exemplary plot of color saturation plotted against the lightness of that color for an idealized RGBW color filter array.

[0032]   Figure 6 comprises an exemplary schematic diagram illustrating the layout of sub-pixels, according to one set of embodiments.

[0033]   Figure 7 comprises, according to one set of embodiments, an exemplary schematic section through a color electrophoretic display comprising a tetrachromatic color filter array.

[0034]   As previously mentioned, color filter arrays comprising four primary colors are provided. Also provided are electro-optic displays using such color filter arrays.

[0035]   The color filter arrays described herein can be produced by selecting four primary color hues, referred to as P1, P2, P3, and P4 herein. Hues P1-P4 can include two pairs of hues: a first hue pair P1 and P3 (i.e., P1/P3), and a second hue pair P2 and P4 (i.e., P2/P4). In some embodiments, hues P1-P4 can be selected such that each pair of hues averages to a neutral gray. For example, the combination of hues P1 and P3 and/or the combination of hues P2 and P4 can average to gray. Such an effect can be achieved by selecting hues with certain positions on the a*b* plane of the La*b* color space.

[0036]   Figures 3A-3B include exemplary plots of the a*b* plane in the La*b* color space, which can be used to illustrate the selection of hues appropriate for use in various embodiments described herein. As used herein, "La*b* color space" refers to the color coordinate system specified in 1976 by the CIE (Commission Internationale de l'Eclairage, International Commission on Illumination, Vienna, Austria, www.cie.co.at) and described in R. W. G. Hunt, The Reproduction of Colour, Fountain Press, Tolworth, England 1988, pp 114-123. Briefly, the La*b* color space includes three coordinates: L, a*, and b*. The position along the L coordinate indicates the lightness of the color, with L = 0 corresponding to black and L = 100 corresponding to diffuse white. The position along the a* coordinate indicates the position of the color between extremes of red/magenta and cyan/green, with negative values of a* corresponding to relatively cyan/green colors and positive values of a* corresponding to relatively red/magenta colors. Finally, the position along the b* coordinate indicates the position of the color between extremes of blue and yellow, with negative values of b* corresponding to relatively blue colors and positive values of b* corresponding to relatively yellow colors. In Figure 3A, the relative amount of yellow in a hue increases in a direction away from the origin along line 301, the relative amount of red in a hue increases in a direction away from the origin along line 302, relative amount of magenta in a hue increases in a direction away from the origin along line 303. In addition, the relative amount of blue in a hue increases in a direction away from the origin along line 304, the relative amount of cyan in a hue increases in a direction away from the origin along line 305, and the relative amount of green in a hue increases in a direction away from the origin along line 306.

[0037]   As mentioned above, the hues within hue pair P1/P3 (and/or hue pair P2/P4) can be selected such that the pair of hues averages to gray. This effect can be achieved by selecting hues with certain hue angles. As used herein, a "hue angle" is determined by plotting the a* and b* coordinates on the a*b* plane, and calculating the angle between the positive a* axis and the line connecting the plotted coordinate and the origin. The hue angle is calculated by tracing the angle in a counter-clockwise direction when the a* axis is oriented such that it points to the right and the b* axis is oriented such that it points upward. For example, referring to Figure 3A, hue 310 has a hue angle of about 60°, as indicated by angle 320.

[0038]   A pair of hues can average to gray when their hue angles are spaced about 180° apart from each other on the a*b* plane of the La*b* color space. For

example, in Figure 3A, the hues positioned at point 310 (with a hue angle of about 60°) and point 312 (with a hue angle of about 240°) have hue angles spaced about 180° apart from each other on the a*b* plane. Accordingly, the hues corresponding to points 310 and 312 would average to gray. As another example, the hues positioned at point 314 (with a hue angle of about 180°) and point 316 (with a hue angle of about 0°) have hue angles spaced about 180° apart from each other on the a*b* plane. Accordingly, the hues corresponding to points 314 and 316 would average to gray.

[0039]   In some embodiments, the four primary colors in the color filter array can be selected such that they include two hue pairs, each hue pair including hues with hue angles that are spaced about 180° apart from each other on the a*b* plane. For example, in some embodiments, the first hue pair (e.g., P1/P3) can include hues corresponding to points 310 and 312, while the second hue pair (e.g., P2/P4) can include hues corresponding to points 314 and 316.

[0040]   In addition to hue pair 310/312 and hue pair 314/316 in Figure 3A, a variety of other hue pairs can be selected in which the hues average to gray (e.g., for use as hue pair P1/P3 and/or P2/P4). For example, red and cyan, illustrated by points 330 and 332, respectively, have hue angles that are spaced about 180° apart from each other. In addition, green and magenta, illustrated by points 334 and 336, respectively, have hue angles that are spaced about 180° apart from each other. As yet another example, blue and yellow, illustrated by points 338 and 340, respectively, have hue angles that are spaced about 180° apart from each other. In some embodiments, hue pair P1/P3 and/or hue pair P2/P4 can include red/cyan (R/C), green/magenta (G/M) and/or blue/yellow (B/Y). Thus, in some embodiments, hue pairs P1/P3 and P2/P4 can be selected such that one is R/C and the other is G/M; such that one is R/C and the other is B/Y; or such that one is G/M and the other is B/Y.

[0041]   It should be understood that the hue angles of the hues within a hue pair do not have to be spaced exactly 180° apart. For example, a hue pair (e.g., hue pair P1/P3 and/or hue pair P2/P4) can include hues with hue angles that are spaced about 180° ± 10°, about 180° ± 5°, about 180° ± 2°, or about 180° ± 1° apart from each other.

[0042]   In some embodiments, hues P1, P2, P3, and P4 can be selected such that the line connecting P1 to P3 and the line connecting P2 to P4 intersect to form an angle close to a right angle. For example, referring to Figure 3A, the hue corresponding to point 338 can be chosen as P1 and the hue corresponding to point

340 can be chosen as P3. In addition, the hue corresponding to point 314 can be chosen for P2, and the hue corresponding to point 316 can be chosen for P4. In this set of embodiments, line 350 (which connects 338 to 340) and line 352 (which connects 314 to 316) intersect to form an angle of about 90°. As another example, the hue corresponding to point 310 can be chosen as P1, the hue corresponding to point 336 can be chosen as P2, the hue corresponding to point 312 can be chosen as P3, and the hue corresponding to point 334 can be chosen as P4. In this set of embodiments, line 360 (which connects 310 to 312) and line 362 (which connects 334 top 336) intersect to form an angle of about 90°.

[0043]   It should be understood that the angle defined by the lines connecting P1 to P3 and P2 to P4 do not have to form an angle of exactly 90°. For example, in some embodiments, a first line connecting hue P1 to hue P3 and a second line connecting hue P2 to hue P4 can intersect within the a*b* plane of the La*b* color space such that they define angles of no less than about 70°, no less than about 80°, no less than about 85°, no less than about 89°, no less than about 89.5°, or no less than about 89.9°. In some embodiments, the intersection of a first line connecting hue P1 to hue P3 and a second line connecting hue P2 to hue P4 within the a*b* plane of the La*b* color space can define an angle from about 70° to about 110°, from about 80° to about 100°, from about 85° to about 95°, from about 89° to about 91°, from about 89.5° to about 90.5°, or from about 89.9° to about 90.1°. Referring to FIG. 3B, for example, P1 can be chosen to correspond to point 380, P2 can be chosen to correspond to point 381, P3 can be chosen to correspond to point 382, and P4 can be chosen to correspond to point 383. In the set of embodiments illustrated in FIG. 3B, line 390 (joining 380 to 382) and line 392 (joining 381 to 383) form a smallest angle (as indicated by angle 394) of about 80°. In some embodiments, a suitable angle at the intersection of the line connecting P1 to P3 and the line connecting P2 to P4 can be achieved when the hue angle between P1 and P2 is from about 70° to about 110°, from about 80° to about 100°, from about 85° to about 95°, from about 88° to about 92°, or from about 89° to about 91°.

[0044]   In some embodiments, the line connecting hue P1 to P3 and the line connecting hue P2 to hue P4 can intersect near the origin of the a*b* plane of the La*b* color space. For example, in the set of embodiments illustrated in FIG. 3A, lines 350 and 352 intersect at the origin of the a*b* plane. In addition, line 360 and line 362 also intersect at the origin of the a*b* plane. It should be understood,

however, that in some embodiments, the lines might not intersect exactly at the origin of the a*b* plane. For example, in the set of embodiments illustrated in FIG. 3B, line 390 and line 392 intersect at point 395, which lies a distance 396 away from the origin of the a*b* plane. In some embodiments, the distance from the origin of the a*b* plane to the intersection of the lines connecting hue P1 to P3 and hue P2 to hue P4 (e.g., distance 396 in FIG. 3B) can be less than about 20%, less than about 10%, less than about 5%, less than about 2%, or less than about 1% of the shortest of the distances between the origin of the a*b* plane and any of hues P1, P2, P3, and P4 (e.g., dotted lines 401, 402, 403, and 404 in FIG. 3B). For example, in the set of embodiments illustrated in FIG. 3B, dotted lines 401, 402, 403, and 404 represent the distances between the origin and points 380, 381, 382, and 383, respectively. In FIG. 3B, distance 396 is less than about 20% of the length of dotted line 403, which is the shortest of dotted lines 401, 402, 403, and 404.

[0045]   In some embodiments, each hue in the color filter array has a minimum saturation. The saturation of a hue within a sub-pixel can be determined by switching all other sub-pixels to black, and measuring the C* value of the sub-pixel that is not switched to black, wherein C* is calculated as:

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad\qquad [1]$$

[0046]   In some embodiments, each sub-pixel can have a C^* value that is greater than 5 ΔE units from the origin as measured when the other sub-pixels are switched to black. One of ordinary skill in the art would be capable of determining the ΔE value for a given hue.

[0047]   In one set of embodiments, the spectrum of the P1/P3 hue pair can be achieved using a low-pass and a high-pass filter in the visible region of the electromagnetic spectrum (i.e., radiation of wavelengths approximately 400 – 700 nm). In some embodiments, the cut-off wavelength of the low-pass and/or high-pass filter used for the P1 and P3 hues can be located between about 500 nm and about 600 nm, between about 520 nm about 570 nm, or between about 530 nm and about 540 nm. Figure 4A includes an exemplary plot of transmittance as a function of wavelength for an exemplary low-pass filter that can be used for P1, according to some embodiments. Figure 4B includes an exemplary plot of transmittance as a function of wavelength for an exemplary high-pass filter that can be used for P3, according to one set of embodiments. In this case, the cut-off wavelength for each of

the filters illustrated in Figures 4A and 4B is about 535 nm. The P1/P3 pair illustrated in Figures 4A-4B, which bisects the visible spectrum in the mid-green region, does not correspond to any complementary pair of the tristimulus primary colors.

[0048]   The spectrum of the P2/P4 hue pair can be achieved using bandpass filters, in some embodiments. In one set of embodiments, the spectrum of P2 can be created using a single bandpass filter with a passband near the center of the visible spectrum (e.g., between about 490 nm and about 570 nm). Figure 4C includes a plot of transmittance as a function of wavelength for such an exemplary P2 filter. In some cases, the spectrum of P4 can be created using a dual bandpass filter with complementary passbands (e.g., one between about 400 nm and about 490 nm and the other between about 570 nm and about 700 nm). Figure 4D includes a plot of transmittance as a function of wavelength for such an exemplary P4 filter. The filter behavior illustrated in Figures 4C-4D is similar to the green/magenta pair of the tristimulus primary colors. Exemplary commercially-available filters that correspond to the representative ideal spectra illustrated in Figures 4A-4D include, for example, filter 768 for Figure 4A (egg yolk yellow), filter M56 for Figure 4C (magenta 6), filter B06 for Figure 4B (lagoon 6), and filter 738 for Figure 4D (Jas green), each of which is available from Lee Filters, Andover, Hampshire, UK.

[0049]   Figures 5A-5B include plots of a modeled color gamut available from a color filter array according to the embodiments described herein, using the ideal spectra illustrated in Figures 4A-4D, located above an electrophoretic ink with a white state reflectivity of 57% and a contrast ratio of 20:1. In generating the plots in Figures 5A-5B, all other light losses were ignored, to produce a relatively simple model. Two views of the color gamut are shown in Figures 5A and 5B. Figure 5A includes a projection of the color gamut in the a*b* plane, while Figure 5B illustrates the color saturation plotted against the lightness of that color. For comparison, similar plots for an idealized RGBW color gamut (using the same assumptions used to generate Figures 5A-5B) are shown in Figures 5C-5D. The overall volume of the color gamut using the color filter array produced using the filters in Figures 4A-4D is about 25% larger than the volume of the color gamut produced using the conventional RGBW color filter array. In addition, upon comparing Figure 5B with Figure 5D, one can see that the colors obtained using the color filter array including the filters in Figures 4A-4D are brighter (higher in L*) for a given saturation (C*), relative to the colors obtained using the idealized RGBW color filter array.

[0050]   In some embodiments, the sub-pixels of the color filter array can be arranged such that the average color along a line that cross a row or column of sub-pixels is gray. This can be achieved, for example, by arranging the sub-pixels such that, along a row or column (or a plurality of rows or columns, or across substantially all rows and columns), the number of P1 sub-pixels is within 5% of, within 2% of, within 1% of, or substantially the same as the number of P3 sub-pixels and/or the number of P2 sub-pixels is within 5% of, within 2% of, within 1% of, or substantially the same as the number of P4 sub-pixels. Figure 6 includes a schematic top-view of one such color filter array, including an exemplary layout of the sub-pixels. In this layout, each of the vertical lines 602 and each of the horizontal lines 604 passes through the same amount of P1 sub-pixels as P3 sub-pixels, and the same amount of P2 sub-pixels as P4 sub-pixels. Accordingly, each of the vertical and horizontal lines in the color array of Figure 6 averages to 50% gray.

[0051]   Figure 7 of the accompanying drawings includes an exemplary schematic section through a color electrophoretic display (generally designated 700) comprising a tetrachromatic color filter array, according to one set of embodiments. The display of Figure 7 includes a backplane 702. An inverted front plane laminate, as described in the aforementioned United States Patent No. 7,839,564, can be laminated onto backplane 702 in some embodiments. The inverted front plane laminate can comprise a monochrome electrophoretic medium layer 706 having black and white extreme optical states supported by a conductive layer (e.g., indium tin oxide) on film 704 (e.g., a polyethylene terephthalate film) and adhered to backplane 702 via adhesive layer 708. A tetrachromatic color filter array 710 having four primary color areas 721 (which can correspond, for example, to P1), 722 (e.g., P2), 723 (e.g., P3), and 724 (e.g., P4) can be printed or otherwise formed on substrate 712 (e.g., a glass substrate). The color filter array and substrate can then be adhered to film 104, for example, by depositing adhesive layer 714 on color filter array 710 or film 706.

[0052]   Conversion of RGB image data for use with the inventive color filters described herein can be desirable. As described above, in some embodiments, the color filter array can include four hues (P1, P2, P3, and P4), which can be grouped into two hue pairs, P1/P3 and P2/P4, each of which averages to gray. In addition, in some embodiments, the angles between hue angles h1 and h3 and between hue angles h2 and h4 can be close to 90 degrees. Such a set of hues can be described as

"opponent." An opponent color space can consists of 3 pairs of opponent components, one luminance component (O_1), and 2 chrominance components (O_2, O_3).

[0053]   A simple transformation exists from trichromatic input space such as RGB to the opponent color space (O_1, O_2, O_3). If the display primaries qualify as opponent primaries (i.e., if each pair can be combined to neutral, and the hue angle between the axes connecting each pair is sufficiently orthogonal), a simple and unique transformation can be made from the trichromatic input color space to the opponent display color space. This is possible because the transformation into the opponent color space reduces the dimensionality of the chrominance component, for example from 3-D (RGB) to 2-D (O_2, O_3). One basic example of such a transformation for R/G, B/Y follows.

[0054]   If O_2 is the red-green channel, $O_2 = G - R$, and if O_3 is the blue-yellow channel, $O_3 = B - Y = B - (R + G)$.

[0055]   For an arbitrary set of opponent primaries, such as P1/P4 and P2/P3, the RGB input data should first be transformed into device-independent XYZ data, after which, the transformation from XYZ to any opponent color space takes the form:

$$O_2 = P1\text{-}P4, \quad O_3=P2\text{-}P3 \tag{2}$$

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = M \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{3}$$

with M being a 3x3 transformation matrix for which the coefficients have to be determined.

[0056]   Compared to colorimetric transformation and spectral matching, the opponent processing provides a unique and computationally inexpensive transformation from trichromatic input to the opponent display space.

[0057]   All patents and patent publications mentioned herein are incorporated herein by reference in their entirety for all purposes.

CLAIMS

1. A color filter array comprising a plurality of pixels, each pixel comprising:

a first sub-pixel having a first hue P1 positioned at a first hue angle $h1$ in the a*b* plane of the La*b* color space;

a second sub-pixel having a second hue P2 positioned at a second hue angle $h2$ in said a*b* plane;

a third sub-pixel having a third hue P3 positioned at a third hue angle $h3$ in said a*b* plane; and

a fourth sub-pixel having a fourth hue P4 positioned at a fourth hue angle $h4$ in said a*b* plane,

the color filter array being characterized in that the third hue angle $h3$ is equal to $h1 + (180° \pm 10°)$, and the fourth hue angle $h4$ is equal to $h2 + (180° \pm 10°)$ in said a*b* plane; and.

2. A color filter according to claim 1 wherein said third hue angle $h3$ is equal to $h1 + (180° \pm 5°)$ and said fourth hue angle $h4$ equal to $h2 + (180° \pm 5°)$ in said a*b* plane.

3. A color filter according to claim 2 wherein said third hue angle $h3$ is equal to $h1 + (180° \pm 2°)$ and said fourth hue angle $h4$ equal to $h2 + (180° \pm 2°)$ in said a*b* plane.

4. A color filter array according to claim 1 wherein hue pairs P1/P3 and P2/P4 are selected from red/cyan, green/magenta and blue/yellow.

5. A color filter array according to claim 1 wherein a first line connecting hue P1 to hue P3 and a second line connecting hue P2 to hue P4 intersect within the a*b* plane of the La*b* color space so as to define angles of not less than about 70°.

6. A color filter array according to claim 5 wherein said first and second lines define angles of not less than about 80°.

7. A color filter array according to claim 6 wherein said first and second lines define angles of not less than about 85°.

8. A color filter array according to claim 1 wherein the line connecting hue P1 to P3 and the line connecting hue P2 to hue P4 intersect near the origin of the a*b* plane of the La*b* color space such that the distance from the

origin of the a*b* plane to said intersection is less than about 20% of the shortest of the distances from the origin of the a*b* plane to any one of hues P1, P2, P3, and P4.

9.   A color filter array according to claim 1 wherein the angle between hue angle *h1* and hue angle *h2* in said a*b* plane is from about 70° to about 110°.

10.   A color filter array according to claim 1 wherein the hue of each sub-pixel in the color filter array has a C* value greater than 5 ΔE units from the origin of the a*b* plane.

11.   An electro-optic display comprising a color filter according to claim 1, a layer of electro-optic material disposed adjacent the color filter capable of changing its optical state upon application of an electric field thereto, and at least one electrode arranged to apply an electric field to the layer of electro-optic material.

12.   An electro-optic display according to claim 11 wherein the electro-optic material comprises a rotating bichromal member or electrochromic material.

13.   An electro-optic display according to claim 11 wherein the electro-optic material comprises an electrophoretic material comprising a plurality of electrically charged particles disposed in a fluid and capable of moving through the fluid under the influence of an electric field.

14.   An electro-optic display according to claim 13 wherein the electrically charged particles and the fluid are confined with a plurality of capsules or microcells.

15.   An electro-optic display according to claim 13 wherein the electrically charged particles and the fluid are present as a plurality of discrete droplets surrounded by a continuous phase comprising a polymeric material.

16.   An electro-optic display according to claim 13 wherein the fluid is gaseous.

17.   An electronic book reader, portable computer, tablet computer, cellular telephone, smart card, sign, watch, shelf label, and/or flash drive comprising a display according to claim 11.
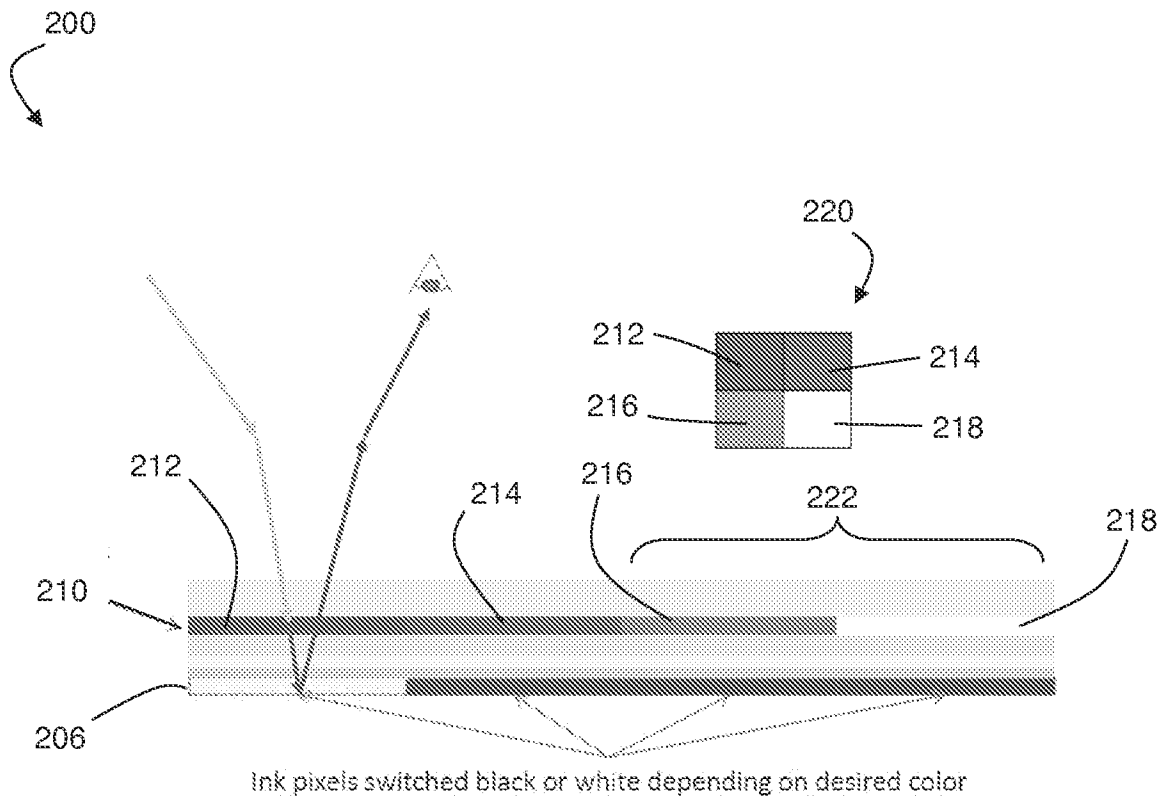
100

112
110
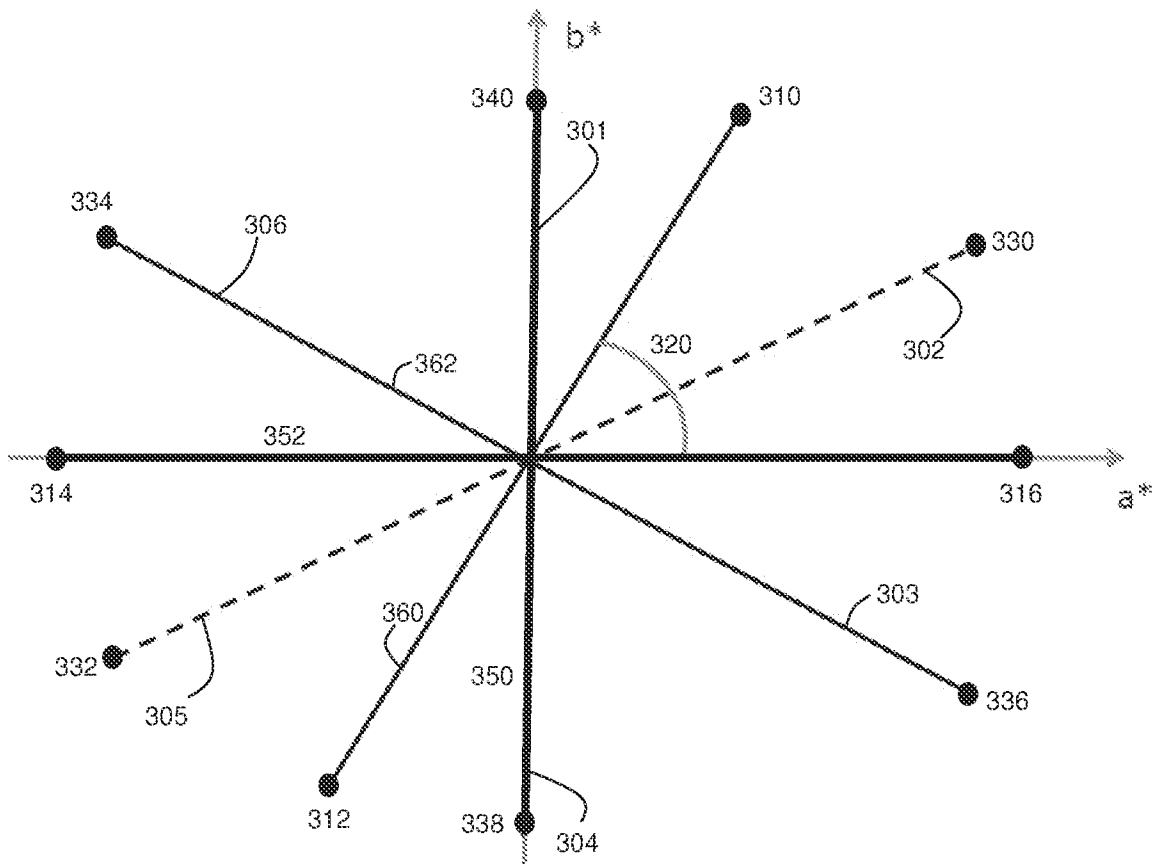114
104
106
108
102

FIG. 1

200

220

212   214

216   218

212   214   216   222   218

210
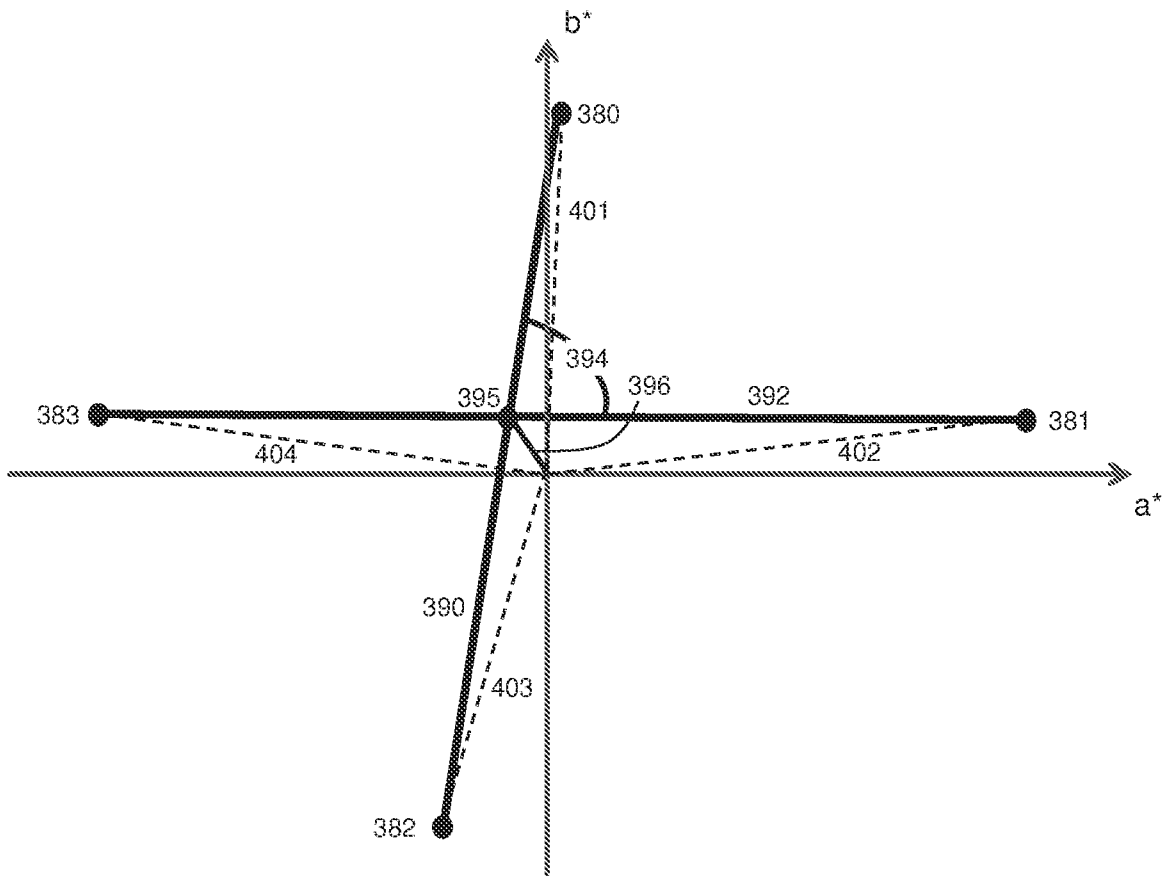
206

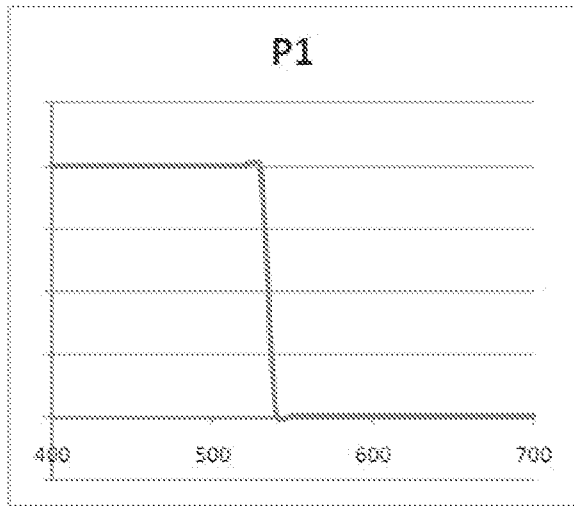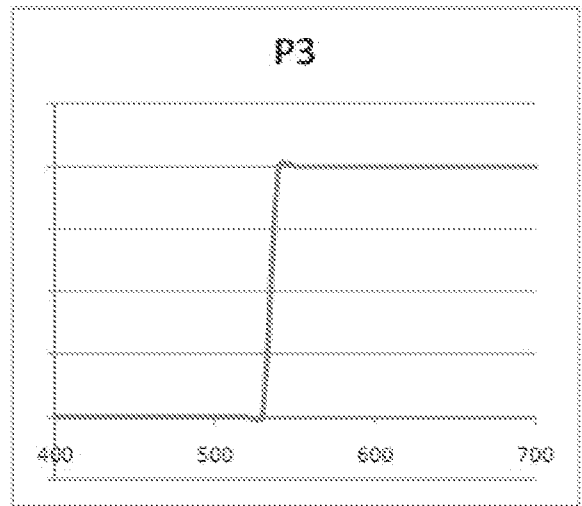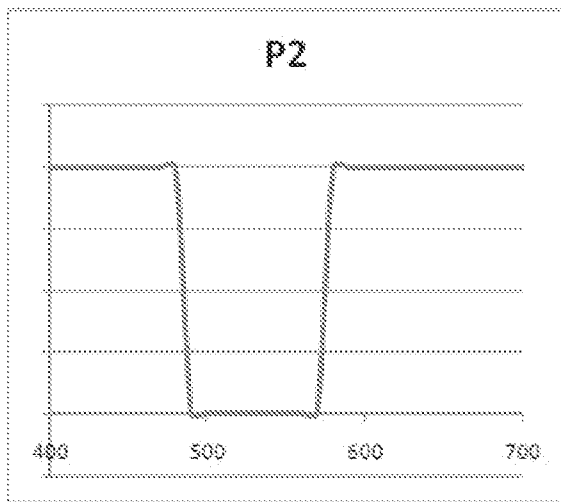Ink pixels switched black or white depending on desired color
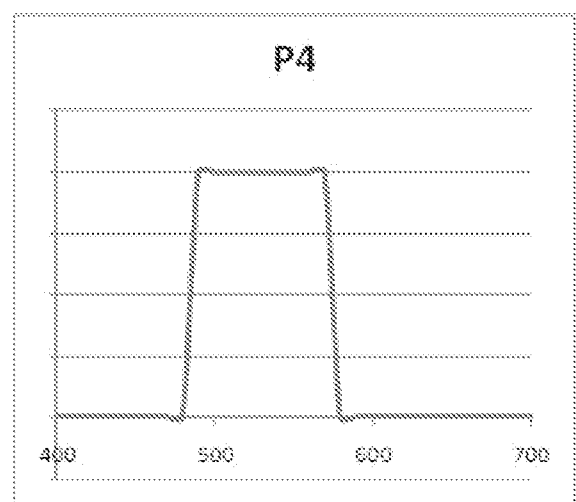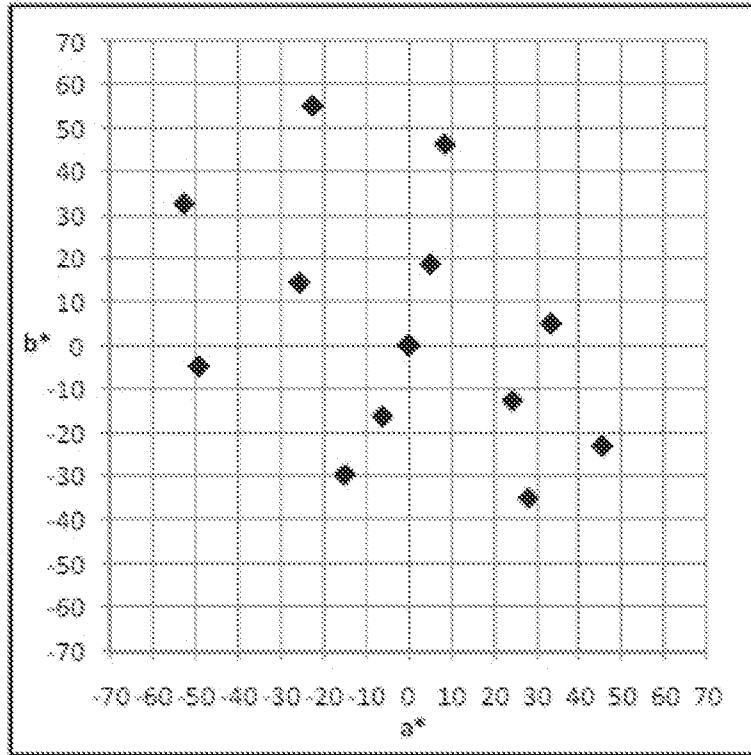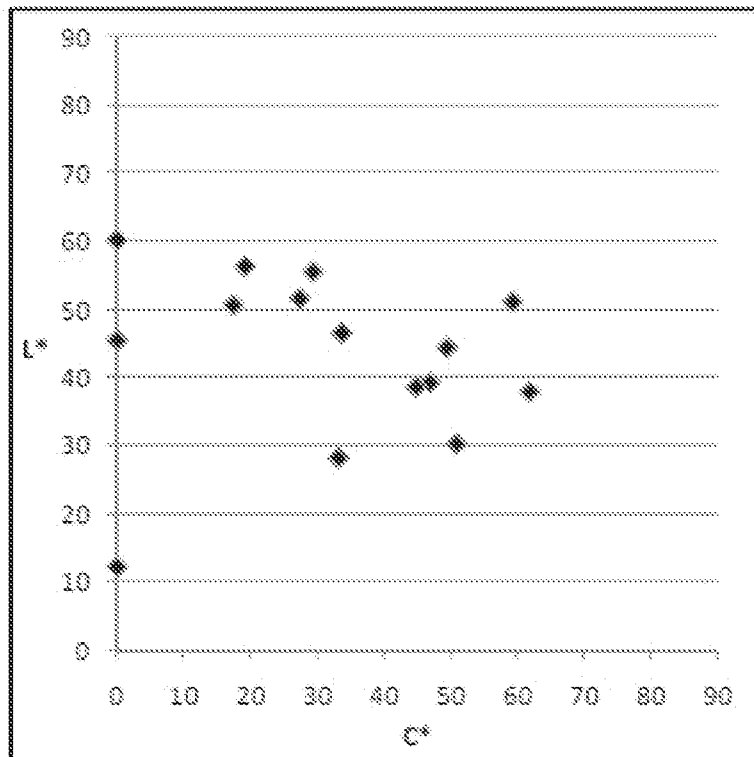
FIG. 2

FIG. 3A

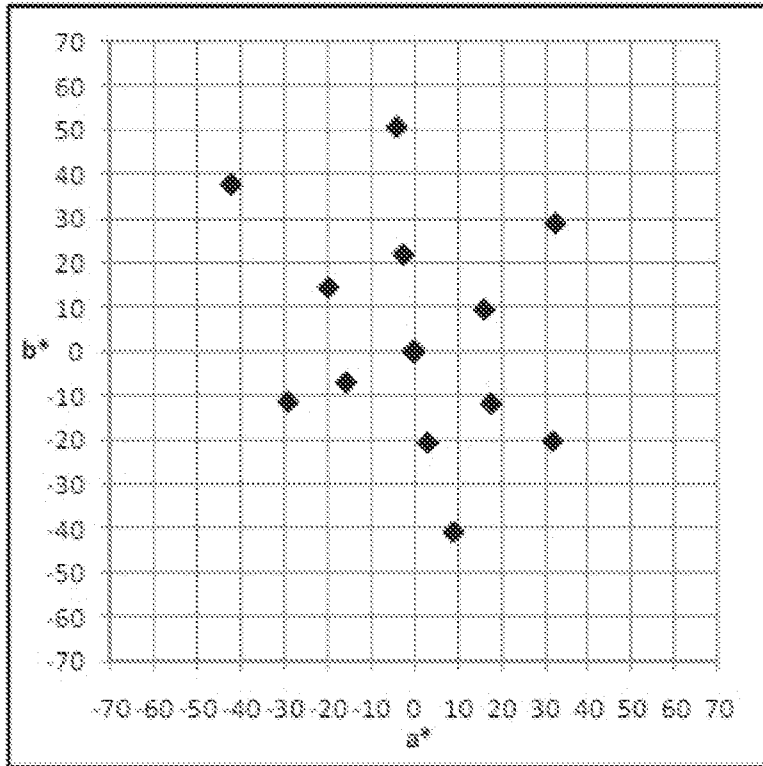4 / 9
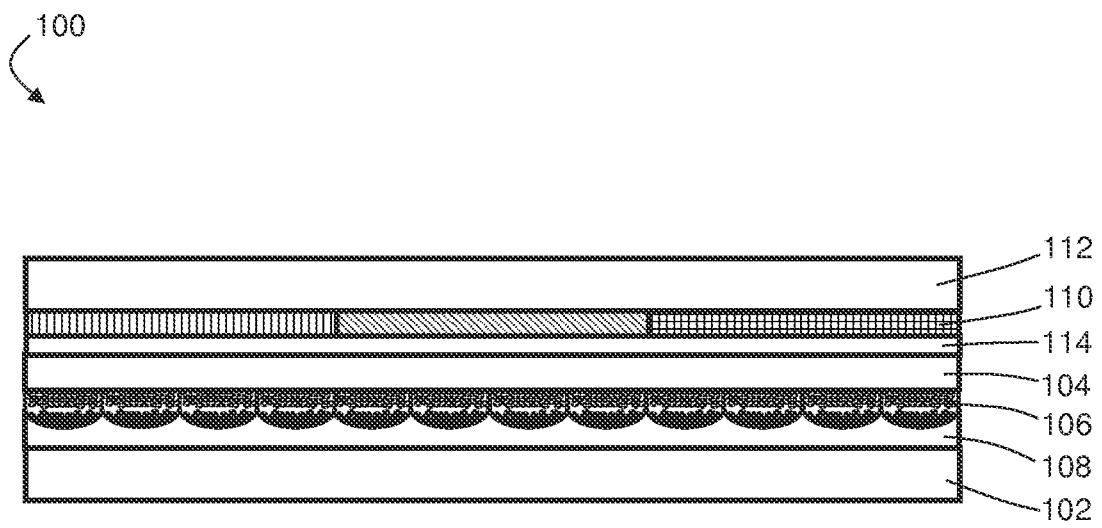
FIG. 3B

FIG. 4A

FIG. 4B

FIG. 4C

FIG. 4D

FIG. 5A

FIG. 5B

FIG. 5C

FIG. 5D

FIG. 6

FIG. 7