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(54) Title: COLOR SENSOR FOR LASER PROJECTOR AND METHODS OF OPERATION

(57) **Abstract:** A method and system are described for setting a color point of a projector. Also a light sensor system is described to sense the color of light, e.g. in a projector as well as a method for processing the light sensor signals. In particular a sensor system and method to determine primary color brightness in white light are described. In particular, a system and method to determine brightness of primary colors in white light used in a single chip laser projector are described. In particular a system and method for controlling display color or brightness of a projector are described.

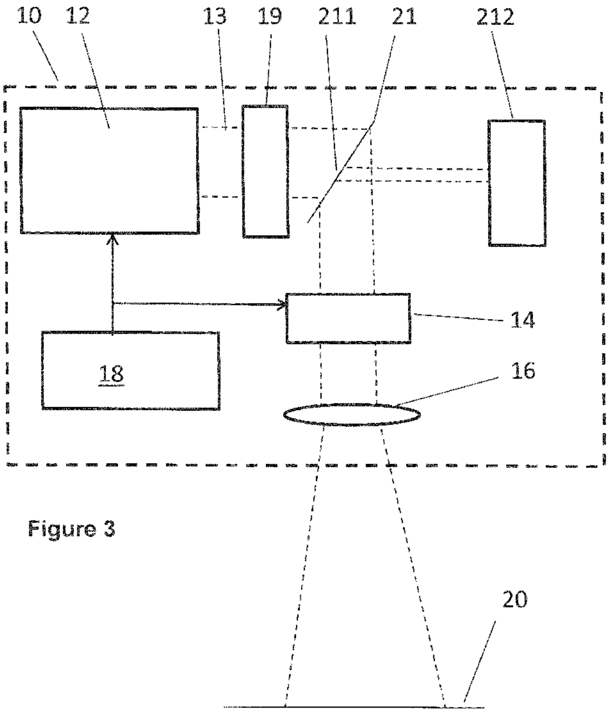

Figure 3

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Color sensor for Laser Projector and methods of operation

The present invention relates to a method and system for setting a color point of a projector, to a light sensor system to sense the color of light, e.g. in a projector and to a method for processing the light sensor signals. In particular the present invention relates in one aspect to a sensor system and method to determine primary color brightness in white light. In particular the present invention relates in another aspect to a system and method to determine brightness of primary colors in white light used in a single chip laser projector. In particular the present invention relates in yet another aspect to a system and method for controlling display color or brightness of a projector.

Background.

Is it known in the art to use a color sensor to enable closed loop control of the color point in emissive displays. The sensors used in such displays are typically based on color filtered photodiodes or mini spectrometers. Solid state light sources like direct laser or LED do not have a stable spectrum in terms of peak wavelength position. Typically there is a spectral shift depending on forward current and junction temperature. Because of that behaviour it is not possible with a three colour sensor such as a tristimulus colorimeter sensor to get sufficient measurement accuracy in colour.

The accuracy of a three color sensor decreases strongly if there is a shift in the spectrum which usually happens when changing forward the current in the laser (e.g. laser diode) or if the temperature of the laser changes.

For LED projectors it can be solved by using an integrated mini-spectrometer and calculating the colour directly from the spectrum. The optical resolution of such devices is >10nm which is still sufficient for LED spectra with a typical bandwidth of 40nm. But in case of laser sources used for projection with 1 to 5nm bandwidth this is not sufficient. Mini-spectrometers do not have the resolution to determine the spectral shift accurately enough.

For applications in which there are several different displays close to each other such as in video walls, the difference in colour of adjacent displays must be very low since the human eye is extremely sensitive to colour difference in the range of $\Delta xy=0{,}002$. For controlling the colour uniformity of a video wall the used measurement device accuracy must be in the same range as this. That is difficult especially for low cost and/or devices which can, for example, be integrated into a projector design.

Figure 1 shows the spectral response of a typical CMOS integrated color sensor. Each colored light R2, B2, G2 (red blue green) is sensed by one or more photodiodes. The wavelength range of light sources B2 and R2 is narrow because they are laser light sources. The range for G2 is broad because this light is generated from a laser incident on a wavelength conversion material such as a phosphor. Each photodiode is covered by an optical filter and is sensitive in a rather large interval of wavelengths R1, G1, B1 (red green blue) and the spectral response of the filtered photodiodes can overlap as seen on figure 1.

The problem of overlapping spectral response can be circumvented as is the case in e.g. LED backlit displays as the one described in US 8175841B2 “Colour feedback with single optical sensor” where as little as one photodiode is used to determine the color point of the light used to illuminate the liquid crystals in a liquid crystal display. To that end, the intensity of light emitted by a primary color light source is evaluated with a single photodiode when the other primary color light sources are inactive.

The solution proposed in the art does not necessarily apply to projectors using laser light sources. For instance, when laser light sources of different primary colors illuminate the same light valve in sequence at frequencies well in excess of 100Hz, the duration of the time interval during which a specific color primary illuminates the light valve can be too small to allow an accurate measurements. Synchronizing measurement with the projector colour sequence fails since no sensor can measure fast enough with sufficient resolution (e.g. 16 bit, 100μs pulse time). Indeed, to achieve a sufficient resolution (e.g. even for 10 bit to encode the output signal of a photodiode dispositive integrating the photocurrent), the integration time should be done over several time intervals during which a given primary color light source is ON. The problem is that if a photodiode used to characterize a given primary color is sensitive to another primary color, keeping integrating the signal through several sequences of primary colors will make it impossible to isolate the contribution of a given primary color light source to the output signal of the photodiode from the contribution to that signal of another primary color light source.

The document EP 2 700 920 “Light sensor system and method for processing light sensor signals” describes a photodiode based color sensor where three photodiodes are used to detect a red component of light, a green component of light and a blue component of light. In addition, a fourth photodiode is used to evaluate the amount of infrared light impinging on the color sensors. A processing unit is configured to correct the signals corresponding to the red component of light, the green component of light and the blue component of light for the infrared light reaching the photodiodes.

EP 2 700 920 does not discuss the influence that e.g. blue light can have on the signal corresponding to a red component of light and does not offer a solution to correct for any overlapping response curves of photodiodes that evaluate different color components of light.

Although individual color sensors could be placed at each color channel before the light is combined in a projector, this can involve altering an existing projector in a significant way. To measure before the light sources are mixed individually to make white light is possible but beside the additional need of three sensors instead of one, there is the difficulty that laser sources are compromising a bigger number of individual laser diodes (e.g. 16 and more) so that proper mixing optics is required to get a representative signal. This will increase cost and complexity significantly and will require more space.

The art needs improvement.

Summary of the invention.

In various aspects the present invention provides a method and system for setting a color point of a projector. In another aspect the present invention provides a light sensor system to sense the color of light, e.g. in a projector as well as a method for processing the light sensor signals. In another aspect the present invention provides a sensor system and method to determine primary color brightness in white light. In another aspect the present invention provides a system and method to determine brightness of primary colors in white light used in a single chip laser projector. In another aspect the present invention provides a system and method for controlling display color or brightness of a projector.

Embodiments of the present invention relate to a light sensor system to sense the color of light, e.g. in a projector and to a method for processing the light sensor signals. Embodiments of the present invention relate to a method and system for setting a color point of a projector, to a light sensor system to sense the color of light, e.g. in a projector and to a method for processing the light sensor signals. In particular embodiments of the present invention relate to a sensor system and method to determine primary color brightness in white light. In particular, embodiments of the present invention relate to a system and method to determine brightness of primary colors in white light used in a single chip laser projector. In particular embodiments of the present invention relate to a system and method for controlling display color or brightness of a projector. Light is sensed after it is mixed and integrated by the illumination optics just before entering an imaging device (e.g. a light valve such as a DMD). Here the light is white and embodiments of the present invention are adapted to obtain the primary color signals from a measurement of the white light. A three color sensor sometimes called a tristimulus colorimeter sensor can be used to measure brightness of the primary colors. Three RGB Sensors of such a colorimeter can be used to determine the color of the primaries with the help of calibration measurements and temperature and laser current information. This means the information one gets from the sensors are nine brightness values for example. Additional information about the primary nominal color and its behaviour with temperature and current can also be taken into account. A suitable sensor can have a spectral response of a typical CMOS integrated color sensor as shown in Figure 1. Each color is sensed by one or more photodiodes. Each photodiode is covered by an optical filter and is sensitive in a rather large interval of wavelengths (R1, B1, G1) and the spectral response of the filtered photodiodes can overlap as seen on Figure 1.

An object of embodiments of the present invention is the provision of a system, device and method to measure a pure primary colours without disturbing the image content.

A light sensor system according to embodiments of the present invention can comprise :

at least a first color sensor to sense light with wavelength in a first wavelength interval and a second color sensor to sense light with wavelength in a second wavelength interval, the first and second intervals overlapping (but not being identical) and the first and second color sensors generating a first and second color channel signal, respectively;

and

a processing unit characterized in that the processing unit is configured to generate a corrected first color channel signal and a corrected second color channel signal according to the formulas

$$O_c = M\,O$$

Where M is a NXN matrix where N is the number of color channel signals, O_c are the $N \geq 2$ corrected color channel signals and O are the N>=2 color channel signals generated by the $N \geq 2$ color sensors.

The photometric brightness can be gained by the sensor raw value multiplied with calibration factors. An example of such factors is given by:

$$Y_{\underline{r}} = R_r \cdot C_r \cdot C_{wl,r};\ \ Y_g = G_g \cdot C_g \cdot C_{wl,g};\ Y_b = B_b \cdot C_b \cdot C_{wl,b}$$

where the C factor is brightness calibration and Cwl is a correction factor of the later in case the wavelength of the related laser source has shifted. Preferably, the related dark current values have been subtracted from the raw values. A photometric brightness for each color channel is preferably calculated by each corrected color channel signal being multiplied by a first factor being a brightness calibration and a second correction factor of a wavelength shift of the first or second color.

The wavelength shift can be determined by the temperature-shift. This factor can be 1 for red if the lasers are driven at constant temperature; 1 for green when a wavelength conversion material such as a phosphor is used since the phosphor spectrum will not shift. The correction for blue is determined out of the photometric brightness change with the wavelength shift.

The primary color itself can be determined by the calibration measurement and forward current and temperature characteristics of laser color.

The system can include primary light sources for primary colors and the system can be configured to isolate contributions of each primary light source to the output color channel signals of the light sensor system from the contributions of other primary light sources. The system can also include a projector which can include a first light source outputting light with a wavelength in a first wavelength interval and a second light source outputting a light with wavelength in a second wavelength interval, the first and second intervals overlapping (but not being identical).

The projector can also include the processing unit configured to generate a corrected first color channel signal and a corrected second color channel signal.

The system also includes means for setting a color point of the projector using the corrected color channel signals.

It is an advantage of the present invention that it improves the control of the color point of images projected by the projector by allowing isolating the contributions of each primary light source to the output signals of the light sensor system from the contributions of the other primary light sources.

In particular, the projector can have three primary light sources and three color sensors. The projector can have a red primary light source, a green primary light source and a blue primary light source. While the red and blue primary light sources each emit light in a narrow interval of wavelengths, the green light source can emit light in a broad interval of wavelength that can include part of the red interval of wavelength and/or the blue interval of wavelengths. It is for instance the case when the green primary light source is a wavelength conversion material such as a phosphor excited by a blue or U.V. laser. Other light sources may be used, e.g. primary color light sources such as RGB light-sources including LEDs or

OLED’s.

The light sensor system can have three color sensors. The light sensor system can have a red color sensor, a green color sensor and a blue color sensor. The color sensors can sense light in overlapping interval of wavelengths.

The light sensor system generates a red channel signal R, a green channel signal G, a blue channel signal B.

The light sensor system has a processing unit configured to generate a corrected red signal R_r, a corrected green signal G_g and a corrected blue signal B_b according to the formulas:

$$\begin{pmatrix} R_r \\ G_g \\ B_b \end{pmatrix} = M \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

where M is a 3X3 matrix.

Embodiments of the present invention also include a method of sensing light comprising :

generating a first and second color channel signal by

sensing first light with wavelength in a first wavelength interval and sensing second light with wavelength in a second wavelength interval, the first and second intervals overlapping and

generating a corrected first color channel signal and a corrected second color channel signal according to the formulas

$O_c = M\,O$

Where M is a NXN matrix where N is the number of color channel signals, O_c are the $N \geq 2$ corrected color channel signals and O are the $N>=2$ color channel signals generated by the $N \geq 2$ color sensors.

A photometric brightness can be gained by the sensor raw value multiplied with calibration factors. An example of such factors is given by:

$$Y_{\underline{r}} = \mathrm{R}_r \cdot C_r \cdot C_{wl,r};\ \ Y_g = G_g \cdot C_g \cdot C_{wl,g};\ Y_b = B_b \cdot C_b \cdot C_{wl,b}$$

where the C factor is brightness calibration and C_{wl} is a correction factor of the later in case the wavelength of the related laser source has shifted. Preferably, the related dark current values have been subtracted from the raw values. A photometric brightness for each color channel is preferably calculated by each corrected color channel signal being multiplied by a first factor being a brightness calibration and a second correction factor of a wavelength shift of the first or second color.

The wavelength shift can be determined by the temperature-shift. This factor can be 1 for red if the lasers are driven at constant temperature; 1 for green when a wavelength conversion material such as a phosphor is used since the phosphor spectrum will not shift. The correction for blue is determined out of the photometric brightness change with the wavelength shift.

The primary color itself can be determined by the calibration measurement and forward current and temperature characteristics of laser color.

The first and second lights can be primary color light of primary colors and the method can be configured to isolate contributions of each primary color light from the contributions of other primary color lights.

The method can also be used for projecting an image. The method can include processing to generate a corrected first color channel signal and a corrected second color channel signal.

The method also includes setting a color point of a projector using the corrected color channel signals.

The method can also include control of the color point of images projected by the projector by allowing isolating of the contributions of each primary light source to the output signals

of the light sensor system from the contributions of the other primary light sources.
Three primary light can be used and three color sensors can be used for the sensing steps. The projector can have a red primary light source, a green primary light source and a blue primary light source. While the red and blue primary light sources each emit light in a narrow interval of wavelengths such as less than 10nm, the green light source can emit light in a broad interval of wavelength such as greater than 10 nm that can include part of the red interval of wavelength and/or the blue interval of wavelengths. It is for instance the case when the green primary light source is a wavelength conversion material such as a phosphor excited by a blue or U.V. laser. Other light sources may be used, e.g. primary color light sources such as RGB light-sources including LEDs or OLED's.

The method can include light sensing by a red color sensor, a green color sensor and a blue color sensor. The color sensors can sense light in overlapping interval of wavelengths.

The method generates a red channel signal R, a green channel signal G, a blue channel signal B.

The processing can generate a corrected red signal R_r, a corrected green signal G_g and a corrected blue signal B_b according to the formulas:

$$\begin{pmatrix} R_r \\ G_g \\ B_b \end{pmatrix} = M \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

where M is a 3X3 matrix.

A photometric brightness can be gained by the sensor raw value multiplied with calibration factors. An example of such factors is given by:

$$Y_r = R_r \cdot C_r \cdot C_{wl,r};\ \ Y_g = G_g \cdot C_g \cdot C_{wl,g};\ Y_b = B_b \cdot C_b \cdot C_{wl,b}$$

where the C factor is brightness calibration and Cwl is a correction factor of the later in case the wavelength of the related laser source has shifted. Preferably, the related dark current values have been subtracted from the raw values. A photometric brightness for each color channel is preferably calculated by each corrected color channel signal being multiplied by a first factor being a brightness calibration and a second correction factor of a wavelength shift of the first or second color.

The wavelength shift can be determined by the temperature-shift. This factor can be 1 for red if the lasers are driven at constant temperature; 1 for green when a wavelength conversion material such as a phosphor is used since the phosphor spectrum will not shift. The correction for blue is determined out of the photometric brightness change with the wavelength shift.

The primary color itself can be determined by the calibration measurement and forward current and temperature characteristics of laser color.

Brief Description of the drawings

Figure 1 shows a spectral response of a typical CMOS integrated color sensor such as TAOS Filter curves compared to RGB spectra that can be used with embodiments of the present invention.

Figure 2 shows a projector suitable for use with embodiments of the present invention.

Figure 3 shows a projector according to an embodiment of the present invention.

Figure 4 shows a calibration procedure for a projector with a set of three primary colors (Red, Green and Blue) according to an embodiment of the present invention.

Figure 5 shows a correction for blue determined out of the photometric brightness change with the wavelength shift as used in embodiments of the present invention.

Figure 6 shows a red laser color current dependency.

Figures 7A and 7B show blue laser color current and temperature dependencies x and y, respectively.

Definitions and acronyms

Illuminance. In photometry, illuminance is the total luminous flux incident on a surface, per unit area. It is a measure of how much the incident light illuminates the surface, wavelength-weighted by the luminosity function to correlate with human brightness perception. Similarly, luminous emittance is the luminous flux per unit area emitted from a surface. Luminous emittance is also known as luminous exitance. In SI derived units these are measured in lux (lx) or lumens per square metre ($cd \cdot sr \cdot m^{-2}$). In the CGS system, the unit of illuminance is the phot, which is equal to 10000 lux. The foot-candle is a non-metric unit of illuminance that is used in photography.

Tristimulus values, represent the weighting of the cones in human eyes. The Y axis represents luminance, the Z axis represents the shortest wavelength at blue, and the X axis is a linear combination of all the cones' response curves. X and Z at any given luminance can then represent any visible color in the spectrum.

Photometric brightness is another term for luminance. The physical measure of *brightness* is *Luminous intensity* per unit projected area of any surface, as measured from a specific direction.

Luminance (usually 'L' in formulas) is the amount of visible *light* leaving a point on a surface in a given direction. This "surface" can be a physical surface or an imaginary plane, and the light leaving the surface can be due to reflection, transmission, and/or emission

Standard unit of luminance is **candela per square meter (cd/m^2)** called **Nits** in the USA.

By "**maximum curren**t" is meant the Maximum Forward Peak Current of a laser diode.

Primary color. One of the colors that is part of the set of colors used to illuminate one of the light valves of the projector. Example: Red, Green and Blue are primary colors in a projector where a red light source, a green light source and a blue light source are used to illuminate the same light valve in sequence or in parallel. Alternatively, each primary colors can illuminate a separate light valve and the light rays re-directed by the separate light valves are combined on screen to form an image.

Description of illustrative embodiments

The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes. Where the term "comprising" is used in the present description and claims, it does not exclude other elements or steps. Furthermore, the terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequential or chronological order. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other sequences than described or illustrated herein.

Figure 2 shows schematically a projection system 5 with which the present invention can be used, comprising a projector 10 and a display surface 20 on which an image is formed. The display surface can be a display screen or some other surface such as a face of a building or water. The projector 10 can be any suitable projector. For example, it can comprise a light source apparatus 12, a spatial light modulator 14 or a light valve and a projection lens assembly 16. The light source apparatus 12 generates a beam 13 of light to illuminate the spatial light modulator 14. The light source apparatus 12 can generate lights from different coloured light sources such as three primary color light sources like e.g. a red laser light source, a green laser light source and a blue laser light source. A green wavelength conversion material such as a green phosphor excited by a UV or blue laser can be used instead of a green laser light source. LEDs of OLED’s or a red wavelength conversion material such as a red phosphor can also be used. The red laser light source can emit light in an interval of wavelengths around 650 nm. The blue laser light source can emit light in an interval of wavelengths around 460 nm. The green wavelength conversion material such as the green phosphor can emit light in a broad interval of wavelength from 480 nm to 680 nm thereby contributing to “red light” and “blue light” illuminating the light valve. The light emitted by the light source can be integrated e.g. to improve the uniformity with which it illuminates the light valve. An integrator 19 in Figure 2, can be e.g. a hollow cylinder with reflective walls or a cylinder made out of a refractive material which receives light at one end and lets light out at another end to illuminate the light modulator 14 or light valve.

The projector can comprise three or more light sources and light valves arranged in parallel - one set for each of the primary colors (e.g. red, green, blue or more), or the same set of light sources and a light valve can be used to sequentially emit each of the primary colors, i.e. red, then green, then blue or more. To obtain special effects or to provide extended color gamut more primary colors can be used. The number of primary colors may be three, four, five or more.

Embodiments of the present invention can have a single integrator, e.g. for a single chip implementation. In embodiments multi-chip and single chip implementations are provided. In a multi-chip implementation, parts can be common and parts can be per primary light source.

Useful combinations are, for example:

- Three or more laser light sources, one integrator, one modulator and the primary colors are projected in time sequence,
- Three or more laser light sources, three or more integrators, three or more modulators,
- Three or more laser light sources, one integrator, three or more modulators.

For example, in a preferred embodiment of the present invention, an architecture with three chips is provided, where each of the chip or spatial light modulator is illuminated by a single primary color. The three single-color images obtained are then merged into one three-color image projected on screen.

The light source apparatus 12 for use with embodiments of the present invention can have one integrator 19 per primary color used. The light sources of the light source apparatus 12 can also include an integrator per primary color (e.g. RGB), the integrator being located (not shown) between the light sources of the light source apparatus 12 and the spatial light modulator 14 or light valve or modulators or valves 14R (for red), 14G (for green) and 14B (for blue).

The spatial light modulator 14 or light valve, can e.g. comprise a two-dimensional array of light modulating elements, also called light valve elements. Each light valve element can correspond to a pixel of the image to be displayed and can be individually controlled to allow an amount of light to pass through/be reflected from or transmitted through that element. In such a spatial light modulator 14 each light valve element can correspond to more than one pixel of the image to be displayed. For example, the spatial light modulator 14 can be controlled, e.g. by oscillating rotation, to allow an amount of light to pass through/be reflected from a pixel element towards a first and a second direction, e.g. to project a pixel in one half of an image and in the other half at different times. Typically, each light valve element is controlled across a range of intensity values (e.g. 256) between 'on' and 'off to provide a range of greyscale values. Such control can include Pulse Width Modulation. The spatial light modulator 14 or light valve can use a transmissive technology, such as liquid crystal panels, in which individual elements are switched on, off or a value somewhere between on and off, depending on the amount of light that is required to be transmitted at that pixel location. Alternatively, the light modulator 14 can use a reflective technology such as a digital micro-mirror device (DMD) in Digital Light Processing (DLP) or Liquid Crystal On Silicon (LCOS).

Advantageously, the light beam 13 has an even intensity distribution across the surface of the spatial light modulator 14 or light valve. The present invention can be used with a variety of light sources including coherent light beams such as those obtained from lasers or narrow band light source likes lasers and LEDs or OLED’s. When a broadband light source is used, the source is preferably filtered spectrally and only selected parts of the spectrum are used. In embodiments of this invention where coherent light is used at least in part, the light source 12 comprises at least one laser light source capable of emitting high-intensity beams of one or more primary colors or a set of laser light sources which are capable of emitting high-intensity beams of one or more primary colors. The light source can for instance comprise a first laser light sources emitting red light with wavelengths distributed around e.g. 635 nm; a second laser light sources emitting blue light with wavelengths distributed around e.g. 470 nm. The light source can also comprise a green light source that relies on a wavelength conversion material such as a phosphor to emit green light. The wavelength conversion material, such as the phosphor, can be excited by the blue laser light or by another light source (e.g. UV light). The light emitted by the wavelength conversion material, such as the phosphor, can have a broader spectrum and emits light predominantly between e.g. 500 nm and 600 nm.

The projector preferably also comprises a controller 18 which controls operation of the light source apparatus 12 and spatial light modulator 14 or light valve. The controller 18 may be supplied as a separate component. The controller can e.g. turn the light sources of the light source apparatus 12 ON and OFF. When the light source apparatus 12 comprises primary color light sources, the controller 18 can turn each primary light source on and off independently of the other primary light sources.

Embodiments of the present invention preferably have a means for directing some light exiting the integrator 19 towards a means for measurement by a color sensor system, as shown schematically in Figure 3. Reference numbers in Figures 2 and 3 which are the same refer to the same components. Figure 3 shows schematically a projection system 5 with which the present invention can be used, comprising a projector 10 and a display surface 20 on which an image is formed. The display surface can be a display screen or some other surface such as a face of a building or water. The projector 10 can be any suitable projector. For example it can comprise a light source apparatus 12, a spatial light modulator 14 or a light valve and a projection lens assembly 16. The light source apparatus 12 generates a beam 13 of light to illuminate the spatial light modulator 14. The light source apparatus 12 can generate lights from different coloured light sources such as three primary color light sources such as, for example, a red laser light source, a green laser light source and a blue laser light source. A green wavelength conversion material such as a green phosphor excited by a UV or blue laser can be used instead of a green laser light source. LEDs of OLED’s or a red wavelength conversion material such as a red phosphor can also be used. The red laser light source can emit light in an interval of wavelengths around 650 nm. The blue laser light source can emit light in an interval of wavelengths around 460 nm. The green wavelength conversion material, such as the green phosphor, can emit light in a broad interval of wavelength from 480 nm to 680 nm thereby contributing to “red light” and “blue light” illuminating the light valve. The light emitted by the light source can be integrated e.g. to improve the uniformity with which it illuminates the light valve. An integrator 19 in Figure

2, can be e.g. a hollow cylinder with reflective walls or a cylinder made out of a refractive material which receives light at one end and lets light out at another end to illuminate the light modulator 14 or light valve.

The projector 10 can comprise three or more light sources and light valves arranged in parallel - one set for each of the primary colors (e.g. red, green, blue or more), or the same set of light sources and a light valve can be used to sequentially emit each of the primary colors, i.e. red, then green, then blue or more. To obtain special effects or to provide extended color gamut, more primary colors can be used. The number of primary colors may be three, four, five or more.

This embodiment of the present invention can have a single integrator, e.g. for a single chip implementation. In embodiments multi-chip and single chip implementations are provided. In a multi-chip implementation, parts can be common and parts can be per primary light source.

Useful combinations are, for example:

- Three or more laser light sources, one integrator, one modulator and the primary colors are projected in time sequence,
- Three or more laser light sources, three or more integrators, three or more modulators,
- Three or more laser light sources, one integrator, three or more modulators.

For example, in a preferred embodiment of the present invention, an architecture with three chips is provided, where each of the chip or spatial light modulator is illuminated by a single primary color. The three single-color images obtained are then merged into one three-color image projected on screen.

The light source apparatus 12 for use with embodiments of the present invention can have one integrator 19 per primary color used. The light sources of the light source apparatus 12 can also include an integrator per primary color (e.g. RGB), the integrator being located (not shown) between the light sources of the light source apparatus 12 and the spatial light modulator 14 or light valve or modulators or valves 14R (for red), 14G (for green) and 14B (for blue).

The spatial light modulator 14 or light valve, can e.g. comprise a two-dimensional array of light modulating elements, also called light valve elements. Each light valve element can correspond to a pixel of the image to be displayed and can be individually controlled to allow an amount of light to pass through/be reflected from or transmitted through that element. In such a spatial light modulator 14 each light valve element can correspond to more than one pixel of the image to be displayed. For example the spatial light modulator 14 can be controlled e.g. by oscillating rotation to allow an amount of light to pass through/be reflected from a pixel element towards a first and a second direction, e.g. to project a pixel in one half of an image and in the other half at different times. Typically, each light valve element is controlled across a range of intensity values (e.g. 256) between 'on' and 'off to provide a range of greyscale values. Such control can include Pulse Width Modulation. The spatial light modulator 14 or light valve can use a transmissive technology, such as liquid crystal panels, in which individual elements are switched on, off or a value somewhere between on and off, depending on the amount of light that is required to be transmitted at that pixel location. Alternatively, the light modulator 14 can use a reflective technology such as a digital micro-mirror device (DMD) in Digital Light Processing (DLP) or Liquid Crystal On Silicon (LCOS).

Advantageously, the light beam 13 has an even intensity distribution across the surface of the spatial light modulator 14 or light valve. The present invention can be used with a variety of light sources including coherent light beams such as those obtained from lasers or narrow band light source likes lasers and LEDs or OLED’s. When a broadband light source is used, the source is preferably filtered spectrally and only selected parts of the spectrum are used. In embodiments of this invention where coherent light is used at least in part, the light source 12 comprises at least one laser light source capable of emitting high-intensity beams of one or more primary colors or a set of laser light sources which are capable of emitting high-intensity beams of one or more primary colors. The light source can for instance comprise a first laser light source emitting red light with wavelengths distributed around e.g. 635 nm; a second laser light source emitting blue light with wavelengths distributed around e.g. 470 nm. The light source can also comprise a green light source that relies on a wavelength conversion material, such as a phosphor, to emit green light. The wavelength conversion material, such as the phosphor, can be excited by the blue laser light or by another light source (e.g. UV light). The light emitted by the wavelength conversion material, such as the phosphor, can have a broader spectrum and emits light predominantly between e.g. 500 nm and 600 nm.

The projector preferably also comprises a controller 18 which controls operation of the light source apparatus 12 and spatial light modulator 14 or light valve. The controller 18 may be supplied as a separate component. The controller can e.g. turn the light sources of the light source apparatus 12 ON and OFF. When the light source apparatus 12 comprises primary color light sources, the controller 18 can turn each primary light source on and off independently of the other primary light sources.

Preferably, the amount of light sent to the sensor system is small, e.g. preferably less than 1% of the light directed towards the light valve 14. For example, a mirror 21 can be positioned between the integrator 19 and the light valve 14. The mirror 21 is a highly reflective mirror (with a reflectivity of at least 99%). The mirror 21 reflects the light exiting the integrator 19 and directs it towards the light modulator 14. The mirror comprises one or more perforations 211 to allow a fraction of the light (preferably less than 1% of the light impinging on the mirror) to pass through the mirror 21 and be available for measurement by a color sensor system 212. The light passing through the perforations in the mirror can be collimated by a lens or array of lenses before being fed to the color sensor system 212. Instead of using a mirror 21 with a whole a very small mirror can be used, e.g. reflecting at most 1% of the light impinging on the light valve.

The color sensor system 212 preferably uses a plurality of photodiodes but other color sensors can be used. A suitable sensor can have a spectral response of a typical CMOS integrated color sensor as shown in Figure 1. Each colored light (R2, B2, G2) is sensed by one or more photodiodes. Each photodiode is covered by an optical filter and is sensitive in a rather large interval of wavelengths (R1, B1, G1) and the spectral response of the filtered photodiodes can overlap as seen on Figure 1. For instance, one photodiode (or group of photodiodes) can be provided per color component: for example, a first (group of) photodiode(s) for Red, a second (group of) photodiode(s) for Green and a third (group of) photodiode(s) for Blue. Each photodiode is covered by a filter. The filters let different wavelengths through as e.g. on the example of Figure 1 ((R1, B1, G1). Each filter transmits predominantly one of the primary colors R. G or B. But the filters not being perfect, they also transmit some of the other primary colors (as illustrated on Figure 1, see R1, B1, G1 ranges which overlap).

Examples of sensors that can be used are the TCS3404 and the TCS3414 digital color sensors from AMS AG, Austria. This sensor has a small sensor area of a few sq.mm. Other commercially available or custom light sensing elements can be used such as active pixel sensors, charged coupled device (CCD) sensors, or other photodetector elements that have suitable characteristics and features necessary to implement the measurements described in embodiments of the present invention.

The sensors such as TCS3404 and TCS3414 derive the color chromaticity and illuminance (intensity) of ambient light and provide a digital output, e.g. with 16-bits of resolution. The devices include an 8 × 2 array of filtered photodiodes, analog-to-digital converters, and control functions on a single monolithic CMOS integrated circuit. Of the 16 photodiodes, 4 have red filters, 4 have green filters, 4 have blue filters, and 4 have no filter (clear). A red filter transmits predominantly red light, a green filter transmits predominantly green light, and a blue filter transmits predominantly blue light. The sensor generates output signals (also known as channels) for the separate groups of photodiodes and colors. The color sensor systems can for instance generate a red channel (output) signal, a green channel (output) signal and a blue channel (output) signal.

In the remainder of the description, it will be assumed that the readings of the color sensor have been corrected for dark current. The dark current R_D, G_D and B_D is preferably evaluated for each of the channels. The dark current is evaluated in absence of light for each of the channels. The absence of light can be achieved e.g. by turning the light source off (which can be done during a black frame insertion when that technique is applied) or by moving a mask in front of the light sensor. The dark current of a photodiode varying exponentially with temperature, it can be measured periodically or in function of measurements of the temperature (a new measurement of the dark current being done whenever the temperature varies by more than a predetermined amount). Alternatively, the dark current can be estimated based on a look-up table or a function that gives a value of dark current for a set of predetermined temperatures. Whenever the dark current must be known, the temperature is measured and the value of the dark current is extracted from the look-up table or is calculated using a function. The output signals R, G and B are available as e.g. analog voltages signals applied to dedicated output pins of a packaged sensor or as binary digits that can be read-out according to manufacturer's instructions.

The output of a given photodiode can be integrated over a time period such as over a time period of several frames.

In embodiments of the present invention, for each primary color, the wavelengths are offset in wavelength from one another. Each wavelength will have a certain spectral distribution around the central wavelength. In at least some embodiments, there are two wavelengths separated by e.g. 25 to 75 nm or 10 to 15 nm for the so called projectors with 6P (6 primary laser lights) or even less.

The output signals R, G and B of the color sensor system used further below are the dark current corrected signal i.e. the output signals of the sensor from which the dark current is subtracted. It is assumed for the complete procedure described below, which is an embodiment of the present invention, that sensor characteristics stay constant over time, e.g. filter and photodiode sensitivity. If this is not the case the color sensor system needs to be recalibrated before the values are used or otherwise corrections must be applied.

Spectral Properties of the light sources

Red Laser

The efficiency of red laser diode can be strongly dependent on the junction or case temperature respectively. Therefore, it is usual to cool the lasers actively to a fixed temperature. For example the temperature can be set and controlled to 25°C±0,5°C. As a consequence no temperature induced color shift can occur. The color change with the diode current is low and the color can be approximated by linear equations:

$$x_r = x_{r,0} + a_{r,x} \cdot (I - I_0) \qquad (1)$$

$$y_r = y_{r,0} + a_{r,y} \cdot (I - I_0) \qquad (2)$$

The dependency can be seen in Figure 6 for the complete current range. The laser regime can start at DAC≈250, when there is a 10 bit resolution for the current.

In practice, the allowed DAC (laser current) range for red laser can be limited in order to keep the laser within the linear operation and to provide a certain lifetime. This range is ~ [320;800] with a 10 bit resolution laser driver. Within this range color coordinates of red laser change by a factor of less than two thousand, which is as small as measurement uncertainty. Hence, the red color dependence on laser current can be neglected. In embodiments of the present invention, color coordinates of a red primary can be considered as constant and need only be measured once during factory calibration.

Green Phosphor

A pure green phosphor spectrum is measured to be independent of temperature and excitation laser power. Experiences with the green Phosphor LED show that also the expected drift over lifetime is in the range of $\Delta xy<1{,}5/1000$. This is at the limit of measurement accuracy of good instruments. Therefore, it is justifiable to set the color of green to be constant:

$$x_g = x_{g,0} \qquad (3)$$

$$y_g = y_{g,0} \qquad (4)$$

Blue laser

The blue laser color is not constant. There are deviations with temperature and diode current. The power is proportional to current and duty cycle. The duty cycle for blue can be fixed to a value such as fixed to 18%. A lower duty cycle is included within the scope of the present invention. A lower duty cycle may be associated with a longer dark time resulting in compensating any brightness win for the two other colors. Hence, in embodiments of the present invention there will be only a current dependency left.

These measured deviations seen in Figures 7A and B can be interpolated again with a linear function like for the red laser. The color changes correspond to a wavelength shift of just <1,5nm which is hard to resolve with a cheap spectrometer capable of being integrated. Therefore, in embodiments of the present invention a linear approximation approach is also applied for blue but extended with a temperature dependency:

$$x_b = x_{b,0} + a_{b,x} \cdot (I - I_0) + b_{b,x} \cdot (T - T_0) \qquad (5a)$$

$$y_b = y_{b,0} + a_{b,y} \cdot (I - I_0) + b_{b,y} \cdot (T - T_0) \qquad (6a)$$

Similar to the red laser, the allowed DAC range for a blue laser is limited within the range ~ [200;760] with 10 bit resolution laser driver. Within this range, color coordinates of a blue laser change by a factor of about 2 thousand, which is inside the measurement uncertainty of ±1 thousand. Blue color dependence on laser current can also be neglected. Otherwise, over the temperature range [10°C;40°C], the blue color coordinates x and y change by 3 and 4 thousands respectively (see Figures 7A and 7B) and are preferably not neglected. Furthermore, it is observed that white color point is sensitive to blue color change. Such a change in blue color primary can induce a change in white color up to a factor of 15 thousand. In embodiments of the present invention, color coordinates of a blue primary are considered as dependent on the temperature of blue laser only. The equations (5a) and (6a) become then:

$$x_b = x_{b,0} + b_{b,x} \cdot T \qquad (5b)$$

$$y_b = y_{b,0} + b_{b,y} \cdot T \qquad (6b)$$

Color Sensor and Measuring

In the beginning of a method according to embodiments of the present invention, the dark current is measured. This is the sensor signal when no light is entering the sensor and it means the current for the laser units is 0. The recorded values are: $R_{DC}; G_{DC}; B_{DC}$. It is preferred to read these values automatically once a projector is started up. In the following considerations, the dark current subtraction is not mentioned explicitly. Any measured signal includes already the dark current subtraction.

The measurement in the projector will be limited to a simple brightness detection of RGB. For that purpose, a Color Sensor from TAOS is a suitable candidate. The advantage of this sensor is that the color filter curve is pretty well aligned to the spectra of RGB. As seen in Figure 1 the sensor signal red is large for red primary and, therefore, used as red brightness sensor. The same is valid for the other two signals green and blue. Since there is no desaturation of primaries by the foreseen current, the three Strobe brightness signals are sufficient to determine the brightness and color of the optical engine in the projector.

To avoid picture disturbance it is preferred if the measurement is synchronized with the strobe signal. However, the resolution of the sensor is dropping if the integration time is reduced to the level of the strobe width. The resolution is preferably ≥ than the 12 bit resolution of the laser driver.

If R’, G’ and B’ are the raw, uncorrected signals given by the color sensor system for the red, green and blue channels (output by light source apparatus 12), the dark current corrected R, G and B signals are given by

$$R = R' - R_D$$

$$G = G' - G_D$$

$$B = B' - B_D$$

where R_D, G_D and B_D are the output signals of the sensor in absence of light for the red, green and blue channel respectively.

The output signals R, G and B generated by the sensor (and corrected for dark current) can be evaluated with the following equations (7a), (7b) and (7c):

$$R = R_r + R_g + R_b \tag{7a}$$

Where R_r is the contribution to the red channel output of the red light source, R_g is the contribution to the red channel output of the green light source (indeed, as discussed earlier, the filter that covers the photodiode of the green channel let some red light through) and R_b is the contribution to the red channel output of the blue light source (indeed, as discussed earlier, the filter that covers the photodiode of the blue channel let some red light through). When the red light is the only light source being activated (e.g. in a calibration phase), we have $R = R_r$.

$$G = G_r + G_g + G_b \tag{7b}$$

Where G_r is the contribution to the green channel output of the red light source, G_g is the contribution to the green channel output of the green light source and G_b is the contribution to the green channel output of the blue light source. We make the assumption that the blue laser light is not used to excite the green wavelength conversion material such as the green phosphor, i.e. a separate blue laser or UV laser source is used to excite the green wavelength conversion material such as the green phosphor.

When the green light is the only light source being activated (e.g. in a calibration phase), we have $G = G_g$.

$$B = B_r + B_g + B_b \tag{7c}$$

Where B_r is the contribution to the blue channel output of the red light source, B_g is the contribution to the blue channel output of the green light source and B_b is the contribution to the blue channel output of the blue light source.

When the blue laser is the only light source being activated (e.g. in a calibration phase), we have $B = B_b$. (here we make the assumption that the blue laser light is not used to excite the green wavelength conversion material such as the green phosphor i.e. a separate blue laser or UV laser source is used to excite the green wavelength conversion material such as the green phosphor).

If we assume that (a) the sensitivity curve of each channel is constant over time and (b) the spectral changes of the lasers (due to e.g. temperature changes) are negligible, equations (7a), (7b) and (7c) can be rewritten as follows:

$$R = R_r + p_{gr}\, G_g + p_{br}\, B_b \qquad (8a)$$

$$G = p_{rg}\, R_r + G_g + p_{bg}\, B_b \qquad (8b)$$

$$B = p_{rb}\, R_r + p_{gb}\, G_g + B_b \qquad (8c)$$

The calibration will deliver a 3*3 matrix of constants p_{ij} giving for each color the proportion of the signal to its main color channel. For example $P_{rg} = G/R$

It is also clear that $p_{rr} = p_{gg} = p_{bb} = 1$;

The equations can be written in matrix notation:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = P \,.\, \begin{pmatrix} Rr \\ Gg \\ Bb \end{pmatrix}$$

$$\text{Where } P = \begin{pmatrix} 1 & pgr & pbr \\ prg & 1 & pbg \\ prb & prb & 1 \end{pmatrix} \qquad (9)$$

Equations (8a), (8b) and (8c) establish a link between the output signal of the R. G and B channels in function of the contributions to the output signals of the R, G and B channels of the corresponding light source.

For instance, R_r can be measured when only the red light source is activated (e.g. the controller 18 turns the green and blue light sources off):
$R = R_r$; $G_g = 0$ and $B_b = 0$

Substituting this result in equations (8b) and (8c) one gets $G = p_{rg} R_r$ and $B = p_{rb} R_r$.

Once the output signals have been measured, it is possible to compute the coefficients $p_{rg} = G / R = G / R_r$ and $p_{rb} = B / R = B / R_r$.

Similarly, when the Green light source is activated and the red and blue light sources are turned off:

$R = p_{gr} G_g$; $G = G_g$ and $B = p_{gb} G_b$.

When the Blue light source is activated and the red and green light sources are turned off:
$R = p_{br} B_b$; $G = p_{bg} B_b$ and $B = B_b$.

Once the coefficients p_{ij} of the matrix P have been determined, it is possible to isolate R_r, G_g and B_b based on the output signals R, G and B when any of the light source is activated alone or together with any of the other light sources. To that end, the matrix P is inverted and R_r, G_b and B_b are given by

$$\begin{pmatrix} R_r \\ G_g \\ B_b \end{pmatrix} = \boldsymbol{P}^{-1} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix} \text{ where } \boldsymbol{P}^{-1} \text{ is the inverse matrix of matrix P.} \qquad (10)$$

While the example is given for a projector using Red, Green and Blue light sources, it is applicable to other sets of primary colors like e.g. {Blue, Yellow} or {Cyan, Magenta, Yellow}.

The photometric brightness is gained by the sensor raw value multiplied with calibration factors:

$$Y_{\underline{r}} = R_r \cdot C_r \cdot C_{wl,r};\ \ Y_g = G_g \cdot C_g \cdot C_{wl,g};\ Y_b = B_b \cdot C_b \cdot C_{wl,b} \qquad (11)$$

where the C factor is brightness calibration and C_{wl} is a correction factor of the later in case the wavelength of the related laser source has shifted. Preferably, the related dark current values have been subtracted from the raw values. A photometric brightness for each color channel is calculated by each corrected color channel signal being multiplied by a first factor being a brightness calibration and a second correction factor of a wavelength shift of the first or second color.

The wavelength shift can be determined by the temperature-shift. This factor can be 1 for red if the lasers are driven at constant temperature; 1 for green when a wavelength conversion material such as a phosphor is used since the phosphor spectrum will not shift. The correction for blue is determined out of the photometric brightness change with the wavelength shift – see Figure 5.

The primary color itself is determined by the calibration measurement and forward current and temperature characteristics of laser color. For example, the color can be determined by the equations (1) to (6). The current and the temperature can be readout and the constants and slope factors are gained from calibration measurements or by a fixed setting. Then, for each color i the number triple Y_i, x_i y_i is available. From that the related related tri-stimulus variables can be calculated:

$$X_r = (x_r/y_r).\ Y_r \ ; \qquad Y_r = Y_r\,; \quad Z_r = ((1-x_r-y_r)/y_r).\ Y_r\,; \qquad (12)$$

$$X_g = (x_g/y_{rg}).\ Y_g \ ; \qquad Y_g = Y_g\,; \quad Z_g = ((1-x_g-y_g)/y_g).\ Y_g\,; \qquad (13)$$

$$X_b = (x_b/y_b).\ Y_b \ ; \qquad Y_b = Y_b\,; \quad Z_b = ((1-x_b-y_b)/y_b).\ Y_b\,; \qquad (14)$$

In embodiments of the present invention, a laser light source can have a threshold current at around 15%-20% of the maximum. Embodiments of the present invention can deal with the threshold itself or the current characteristics when they are not constant. Embodiments of the present invention can deal with a tolerance and a change with lifetime of both parameters.

In embodiments of the present invention, not all lasers of a unit need to be on. It can be avoided that desaturation becomes very inefficient.

Embodiments of the present invention can use Canonical correlation analysis (CCA) and Laser driver current to match color points. Such a process can be realized in two steps. The first step targets the white point coordinate by modulating the Laser current only. A second step, which uses a spatial light modulator such as a DMD, takes the not saturated primaries to the coordinates of the target gamut primaries with the help of CCA. With this combined principle the effect of the CCA part can be much smaller and more balanced for all projectors, leading to a better color and brightness homogeneity compared to the CCA only approach. And the white brightness adjusted via the laser currents will not be affected. The primary adjustment with CCA has no influence on the white point.

White colour

The measured white point is preferably the sum of the related primary values:

$$X_W = \Sigma Xi \; ; \; Y_W = \Sigma Y_i \; ; \; Z_W = \Sigma Z_i \qquad (15)$$

Figure 4 summarizes an example of calibration procedures for a projector with a set of three primary colors (Red, Green and Blue).

Method embodiment

In a first step, a first light source (e.g. the Red laser light source) is turned on while the second and third (e.g. the green wavelength conversion material light source such as the green phosphor light source and the blue laser light source) are turned off. If the red light source is a laser diode, the forward current I_{fwd} in the laser diode is chosen within the interval of forward current that will be used during operation of the projector (i.e. in normal operation by an end-user). For instance, if the forward current can vary between a lower limit $I_{fwd\ min}$ and an upper limit $I_{fwd\ max}$, the forward current is taken as the average value ($I_{fwd\ max} + I_{fwd\ min}$) / 2.

In a second step, the output signal of each color channel of the color sensor is read-out and corrected for Dark Current: R = R' – RD; G = G'- GD; B = B'- BD.

In a third step, the two first elements of the P matrix are computed:

$$p_{rg} = G / R \text{ and } p_{rb} = B / R.$$

In a fourth step, the second light source is activated and the first and third light sources are turned off.

In a fifth step, the output signal of each color channel of the color sensor is read-out and corrected for Dark Current: R = R' – RD; G = G'- GD; B = B'- BD.

In a sixth step, the next two elements of the P matrix are computed:

$$p_{gr} = R / G \text{ and } p_{gb} = B / G.$$

In a seventh step, the third light source is activated and the first and second light sources are turned off.

In an eighth step, the output signal of each color channel of the color sensor is read-out and corrected for Dark Current: R = R' – RD; G = G'- GD; B = B'- BD.

In a ninth step, the last two elements of the P matrix are computed:

$$p_{br} = R / G \text{ and } p_{bg} = B / G.$$

Once the elements of the P matrix have been determined, the matrix is inverted and its element stored in memory.

Each time the output signals of the color sensor system are read-out, the results can be stored in a memory associated with the processing unit.

The elements of the P matrix can also be stored in the same memory associated with the processing unit.

In addition to characterizing the color sensor that monitors the light illuminating the light valve, it may also be necessary to control what happens on screen.

To avoid having to rely on an additional photometer outside of the projector, the following steps can be taken to use the readings of the color sensor to evaluate the illuminance based on measurements taken during a calibration phase.

In a first step, the red light source is activated. If the red light source is a laser diode, the forward current I_{fwd} in the laser diode is chosen within the interval of forward current that will be used during operation of the projector (i.e. in normal operation by an end-user). For instance, if the forward current can vary between a lower limit $I_{fwd\ min}$ and an upper limit $I_{fwd\ max}$, the forward current is taken as the average value $(I_{fwd\ max} + I_{fwd\ min}) / 2$.

The spatial light modulator or light valve is configured to re-direct the light rays towards the projection optics. For instance, if the light valve is a DMD, all pixels are set to ON. The illuminance E_r is measured on the screen with a photometer. The output signal R_r of the red channel (with dark current correction) is read-out and a coefficient Cr is evaluated:

- Switch on the Red laser channel only with a DAC value such as 768; wait a period such as 30 seconds for stabilization; Read out sensor signal: $\widetilde{R_g} = \tilde{R}$
    - Measure on screen illuminance E_r. $C_r = \frac{E_r}{\widetilde{R_r}}$
    - Measure the color on screen $x_{r,0}, y_{r,0}$

The period of waiting time depends on the laser type and the cooling and must be evaluated case to case.

- Switch on the Green laser channel only with a DAC value such as 768; wait a period of time such as a period of 30 seconds for stabilization; Read out sensor signal: $\widetilde{G_g} = \tilde{G}$

  - Measure on screen illuminance E_g. $C_g = \frac{E_g}{\widetilde{G_g}}$
  - Measure the color on screen $x_{g,0}, y_{g,0}$

The waiting time depends on the laser type and the cooling and must be evaluated case to case.

- Switch on the Blue laser channel only with a DAC value such as 768; wait a period of time such as a period of 30 seconds for example or stabilization; Read out sensor signal: $\widetilde{B_b} = \tilde{B}$
  - Measure on screen illuminance E_b. $C_b = \frac{E_b}{\widetilde{B_b}}$
  - Measure the color on screen $x_{b,0}, y_{b,0}$

The period of waiting time depends on the laser type and the cooling and must be evaluated case to case.

Embodiments of the present invention can control the color point of images projected by the projector by allowing isolation of the contributions of each primary light source to the output signals of the light sensor system from the contributions of the other primary light sources. From tristimulus color theory one can calculate the color and brightness of white if one knows the brightness of the primaries and their colour point. The color point can be obtained from calibration and characteristics information. A given color point can be realized by pulse modulation, e.g. PWM of the micro-mirror movements, e.g. at a frequency in the kHz range. Electronic dimming of an image while keeping the color point constant would require operation of the lasers at a PWM frequency far higher than 1kHz. Such high switching speeds are deemed impractical in a projector. Mechanical dimming, e. g. using an iris, is not a preferred solution: light is absorbed by the iris and the temperature of the iris as well as the inside of the projector can increase beyond acceptable limits as well as the waste of energy.

Reducing the current in the laser is not practical below a given limit. Indeed, a semi-conductor laser has a certain threshold current before it can start emitting laser light. For common semi-conductor lasers suitable for projection, this threshold current is close to 20%

of the maximum current. The threshold can significantly differ between different diodes. The threshold current is also drifting to higher values with the lifetime. It also fluctuates with temperature.

Therefore, to avoid that a laser diode operates outside of the spontaneous excited emission, the laser diodes should be driven at least 25% above their threshold to avoid the slip below the threshold. It is even favorable to go higher to be more power efficient.

Methods according to the present invention can be performed by a control unit 18 shown in Figure 2 or Figure 3, either as a standalone device or embedded in a projector or as part of an optical subsystem for a projector. The present invention can use a processing engine to carry out functions. The processing engine preferably has processing capability such as provided by one or more microprocessors, FPGA's, or a central processing unit (CPU) and/or a Graphics Processing Unit (GPU), and which is adapted to carry out the respective functions by being programmed with software, i.e. one or more computer programs. References to software can encompass any type of programs in any language executable directly or indirectly by a processor, either via a compiled or interpretative language. The implementation of any of the methods of the present invention can be performed by logic circuits, electronic hardware, processors or circuitry which can encompass any kind of logic or analog circuitry, integrated to any degree, and not limited to general purpose processors, digital signal processors, ASICs, FPGAs, discrete components or transistor logic gates and similar.

Such a controller 18 may have memory (such as non-transitory computer readable medium, RAM and/or ROM), an operating system, optionally a display such as a fixed format display, ports for data entry devices such as a keyboard, a pointer device such as a "mouse", serial or parallel ports to communicate other devices, network cards and connections to connect to any of the networks.

The software can be embodied in a computer program product adapted to carry out the functions of any of the methods of the present invention, e.g. as itemised below when the software is loaded onto the controller and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc. Hence a controller 18 for use with any of the embodiments of the present invention can incorporate a computer system capable of running one or more computer applications in the form of computer software.

The methods described with respect to embodiments of the present invention above can be performed by one or more computer application programs running on the computer system by being loaded into a memory and run on or in association with an operating system such as Windows^{TM} supplied by Microsoft Corp, USA, Linux, Android or similar. The computer system can include a main memory, preferably random access memory (RAM), and may also include a non-transitory hard disk drive and/or a removable non-transitory memory, and/or a non-transitory solid state memory. Non-transitory removable memory can be an optical disk such as a compact disc (CD-ROM or DVD-ROM), a magnetic tape, which is read by and written to by a suitable reader. The removable non-transitory memory can be a computer readable medium having stored therein computer software and/or data. The non-volatile storage memory can be used to store persistent information that should not be lost if the computer system is powered down. The application programs may use and store information in the non-volatile memory.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

turning on a first light source (e.g. the Red laser light source) on while a second and a third (e.g. the green wavelength conversion material light source such as the green phosphor light source and the blue laser light source) are turned off.

If the red light source is a laser diode, the forward current I_{fwd} in the laser diode is controlled within an interval of forward current that will be used during operation of the projector (i.e. in normal operation by an end-user).

Optionally, if the forward current can vary between a lower limit $I_{fwd\ min}$ and an upper limit $I_{fwd\ max}$, the forward current is taken as the average value $(I_{fwd\ max} + I_{fwd\ min}) / 2$.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

the output signal of each color channel of the color sensor is read-out and corrected for Dark Current: $R = R' - RD$; $G = G' - GD$; $B = B' - BD$.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

the two first elements of the P matrix are computed:

$$p_{rg} = G / R \text{ and } p_{rb} = B / R.$$

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

the second light source is activated and the first and third light sources are turned off.

the output signal of each color channel of the color sensor is read-out and corrected for Dark Current: $R = R' - RD$; $G = G' - GD$; $B = B' - BD$.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

the next two elements of the P matrix are computed:

$$p_{gr} = R / G \text{ and } p_{gb} = B / G.$$

the third light source is activated and the first and second light sources are turned off.

the output signal of each color channel of the color sensor is read-out and corrected for Dark Current: R = R' – RD; G = G'- GD; B = B'- BD.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

the last two elements of the P matrix are computed:

$$p_{br} = R / G \text{ and } p_{bg} = B / G.$$

Once the elements of the P matrix have been determined, the matrix is inverted and its element stored in memory.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

Each time the output signals of the color sensor system are read-out, the results are stored in a memory associated with the processing unit.

The elements of the P matrix are stored in the same memory associated with the processing unit.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

In addition to characterizing the color sensor that monitors the light illuminating the light valve, what happens on screen is controlled.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

The following steps can be taken to use the readings of the color sensor to evaluate the illuminance based on measurements taken during a calibration phase.

The red light source is activated. If the red light source is a laser diode, the forward current I_{fwd} in the laser diode is chosen within the interval of forward current that will be used during operation of the projector (i.e. in normal operation by an end-user). For instance, if the forward current can vary between a lower limit $I_{fwd\ min}$ and an upper limit $I_{fwd\ max}$, the forward current is taken as the average value $(I_{fwd\ max} + I_{fwd\ min}) / 2$.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

The light valve is configured to re-direct the light rays towards the projection optics. For instance, if the light valve is a DMD, all pixels are set to ON.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

The illuminance E_r is measured on the screen with a photometer. The output signal R_r of the red channel (with dark current correction) is read-out and a coefficient Cr is evaluated:
The Red laser channel only is switched on with a DAC value such as 768; a time period is waited such as 30 seconds for stabilization; Sensor signal: $\widetilde{R_g} = \tilde{R}$ is read out.

on screen illuminance E_r. $C_r = \frac{E_r}{\widetilde{R_r}}$ is measured the color on screen $x_{r,0}, y_{r,0}$ is measured

The Green laser channel only is switched on with a DAC value such as 768; a period is waited such as 30 seconds for stabilization; sensor signal: $\widetilde{G_g} = \tilde{G}$ is read out

On screen illuminance E_g. $C_g = \frac{E_g}{\widetilde{G_g}}$ is measured

The color on screen $x_{g,0}, y_{g,0}$ is measured

The Blue laser channel only is switched on with a DAC value such as 768; a period is waited such as 30 seconds for stabilization; sensor signal: $\widetilde{B_b} = \tilde{B}$ is read out.

On screen illuminance E_b. ⇨ $C_b = \frac{E_b}{\widetilde{B_b}}$ is measured

The color on screen $x_{b,0}, y_{b,0}$ is measured.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

control of the color point of images projected by a projector by allowing isolation of the contributions of each primary light source to the output signals of the light sensor system from the contributions of the other primary light sources.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

generating a first and second color channel signal by sensing first light with wavelength in a first wavelength interval and sensing second light with wavelength in a second wavelength interval, the first and second intervals overlapping;

generating a corrected first color channel signal and a corrected second color channel signal according to the formula

$$O_c \ = M \ O$$

where M is a NXN matrix where N is the number of color channel signals, O_c are the $N \geq 2$ corrected color channel signals and O are the N>=2 color channel signals generated by the $N \geq 2$ color sensors.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

A photometric brightness for each color channel is calculated by each corrected color channel signal being multiplied by a first factor being a brightness calibration and a second correction factor of a wavelength shift of the first or second color.

Calculating $Y_{\underline{r}} = R_r \cdot C_r \cdot C_{wl,r}$; $Y_g = G_g \cdot C_g \cdot C_{wl,g}$; $Y_b = B_b \cdot C_b \cdot C_{wl,b}$.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

The first and second lights are primary color lights of primary colors and contributions of each primary color light are isolated from the contributions of other primary color lights in the first color channel signal and the corrected second color channel.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.: processing to generate a corrected first color channel signal and a corrected second color channel signal.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

setting a color point of a projector using the corrected color channel signals.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

three primary lights are sensed by three color sensors;
wherein light sensing is by a red color sensor, a green color sensor and a blue color sensor, whereby the color sensors can sense light in overlapping interval of wavelengths;

the three primary lights are emitted by a red primary light source, a green primary light source and a blue primary light source, the red and blue primary light sources each emitting light in a narrow interval of wavelengths such as less than 10 nm, and the green light source emitting light in a broad interval of wavelength such as greater than 10 nm that can include part of the red interval of wavelength and/or the blue interval of wavelengths.

The software embodied in the computer program product is adapted to carry out the following functions when the software is loaded onto the respective device or devices and executed on one or more processing engines such as microprocessors, ASIC's, FPGA's etc.:

generating a red channel signal R, a green channel signal G, a blue channel signal B, whereby the processing step generates a corrected red signal R_r, a corrected green signal G_g and a corrected blue signal B_b according to the formulas:

$$\begin{pmatrix} R_r \\ G_g \\ B_b \end{pmatrix} = M \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

where M is a 3X3 matrix;

generating a color point using the corrected red, green and blue signals.

Claims

1. A light sensor system comprising :
at least a first color sensor to sense first light with wavelength in a first wavelength interval of a first light source and a second color sensor to sense second light with wavelength in a second wavelength interval of a second light source, the first and second wavelength intervals are overlapping but not being identical and the first and second color sensors generating a first and second color channel signal, respectively; and

a processing unit characterized in that the processing unit is configured to generate a corrected first color channel signal and a corrected second color channel signal according to the formula:

$O_c = M\ O$

where M is a NXN matrix where N is the number of color channel signals, O_c are the $N \geq 2$ corrected color channel signals and O are the N>=2 color channel signals generated by the $N \geq 2$ color sensors, a photometric brightness for each color channel being given by each corrected color channel signal being multiplied by a first factor being a brightness calibration and a second correction factor of a wavelength shift of the first or second color.

2. The light sensor system according to claim 1, wherein the photometric brightness is given by

$$Y_r = \tilde{R}_r \cdot C_r \cdot C_{wl,r}; \qquad Y_g = \tilde{G}_g \cdot C_g; \qquad Y_b = \tilde{B}_b \cdot C_b \cdot C_{wl,b}$$

3. The light sensor system according to claim 1 or 2, further comprising primary light sources for primary colors wherein the system is configured to isolate contributions of each primary light source to the output color channel signals of the light sensor system from the contributions of other primary light sources.

4. The light sensor system according to any previous claim, further comprising a first laser light source outputting the first light and a second laser light source outputting the second light.

5. The light sensor system according to any previous claim, further comprising means for setting a color point of a projector using the corrected color channel signals.

6. The light sensor system according to any previous claim, comprising a red color sensor, a green color sensor and a blue color sensor, whereby the color sensors sense light in overlapping interval of wavelengths.

7. The light sensor system according to claim 6, wherein the red color sensor generates a red channel signal R, the green color sensor generates a green channel signal G, the blue color sensor generates a blue channel signal B.

8. The light sensor system according to any previous claim, wherein the processing unit is configured to generate a corrected red signal R_r, a corrected green signal G_g and a corrected blue signal B_b according to the formulas:

$$\begin{pmatrix} R_r \\ G_g \\ B_b \end{pmatrix} = M \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

where M is a 3X3 matrix.

9. The light sensor system according to claim 7 or 8, comprising a red primary light source, a green primary light source and a blue primary light source, the red and blue primary light sources each emitting light in a less than 10nm interval of wavelengths, the green light source emitting light in a broad interval of wavelengths greater than 10nm that can include part of the red interval of wavelength and/or the blue interval of wavelengths.

10. The light sensor system of claim 9, wherein the green primary light source is a wavelength conversion material excited by a blue or UV laser.

11. The light sensor system of claim 9, wherein any of the red primary light source, the green primary light source and the blue primary light source can be lasers, LEDs or OLED’s.

12. A projector with the light system of any of the claims 1 to 11.

13. A method of sensing light comprising :

generating a first and second color channel signal by

sensing a first light with a wavelength in a first wavelength interval and sensing a second light with a wavelength in a second wavelength interval, wherein the first and second intervals overlap and

generating a corrected first color channel signal and a corrected second color channel signal according to the formula

$O_c = M\,O$

where M is a NXN matrix where N is the number of color channel signals, O_c are the $N \geq 2$ corrected color channel signals and O are the N>=2 color channel signals generated by the $N \geq 2$ color sensors, a photometric brightness for each color channel being calculated by each corrected color channel signal being multiplied by a first factor being a brightness calibration and a second correction factor of a wavelength shift of the first or second color.

14. The method of claim 13, wherein the photometric brightness is given by

$$Y_r = \tilde{R}_r \cdot C_r \cdot C_{wl,r}; \qquad Y_g = \tilde{G}_g \cdot C_g; \qquad Y_b = \tilde{B}_b \cdot C_b \cdot C_{wl,b}.$$

15. The method of claim 13 or 14, wherein the first and second lights are primary color lights of primary colors and the method isolates contributions of each primary color light from the contributions of other primary color lights in the first corrected color channel signal and the second corrected color channel signal.

16. The method according to claim 14 or 15, further comprising processing to generate a first corrected color channel signal and a second corrected color channel signal.

17. The method according to claim 16, further comprising setting a color point of a projector using the corrected color channel signals.

18. The method of any of the claims 15 to 17, wherein three primary lights are sensed by three color sensors.

19. The method of claim 18, wherein light sensing is by a red color sensor, a green color sensor and a blue color sensor, whereby the color sensors can sense light in overlapping interval of wavelengths.

20. The method of claim 18 or 19, the three primary lights are emitted by a red primary light source, a green primary light source and a blue primary light source.

21. The method of claim 20, further comprising the red and blue primary light sources each emitting light in an interval of wavelengths less than 10 nm, and the green light source emitting light in a broad interval of wavelengths greater than 10 nm that can include part of the red interval of wavelengths and/or the blue interval of wavelengths.

22. The method according to any of the claims 13 to 21, comprising generating a red channel signal R, a green channel signal G, a blue channel signal B, whereby the processing step generates a corrected red signal R_r, a corrected green signal G_g and a corrected blue signal B_b according to the formulas:

$$\begin{pmatrix} R_r \\ G_g \\ B_b \end{pmatrix} = M \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

where M is a 3x3 matrix.

23. The method of claim 22, further comprising generating a color point using the corrected red, green and blue signals.

24. A computer program product which when executed on a processor carries out any of the methods according to claim 13 to 23.

25. A non-transitory signal storing means storing the computer program of claim 24.

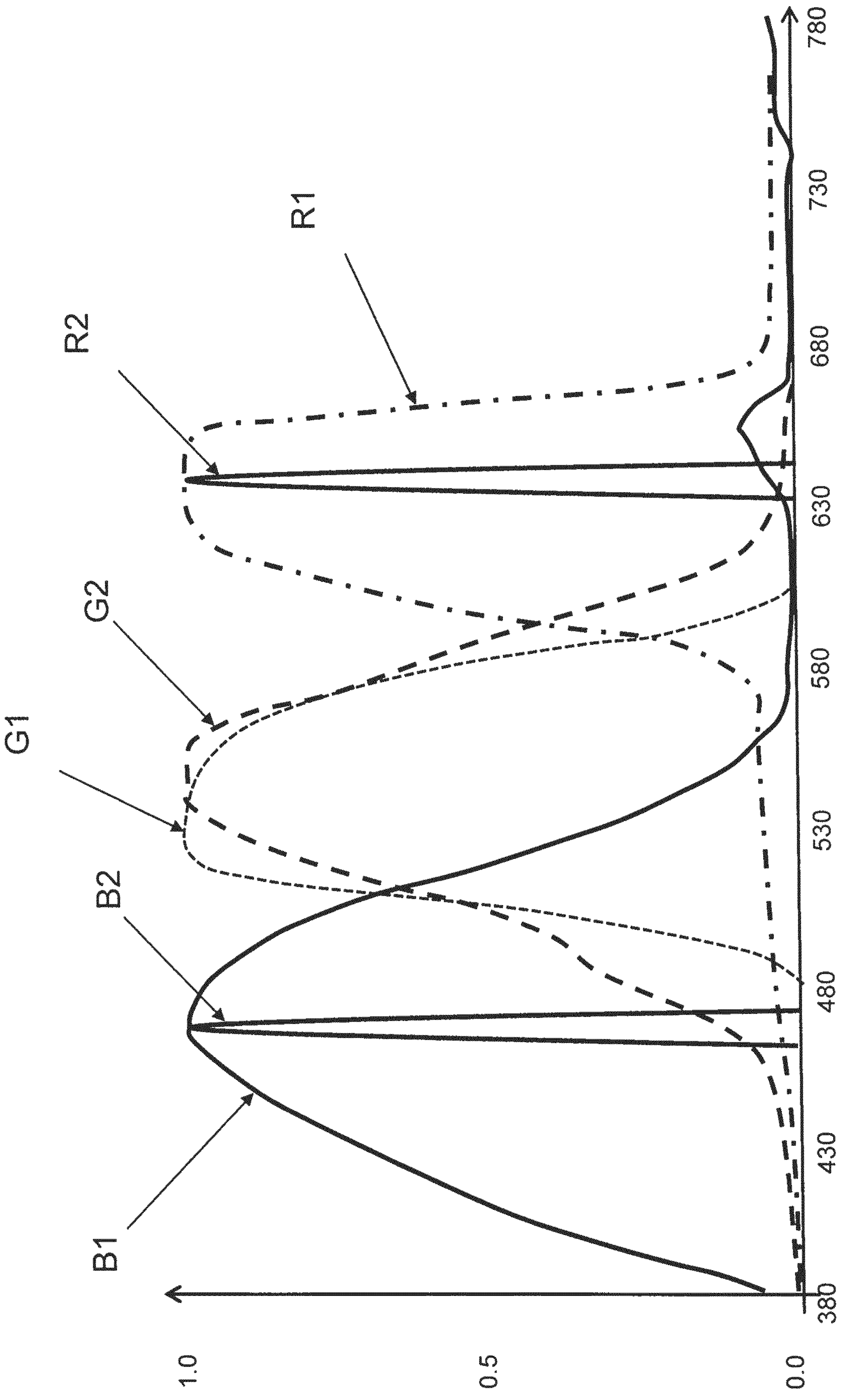


Figure 1.

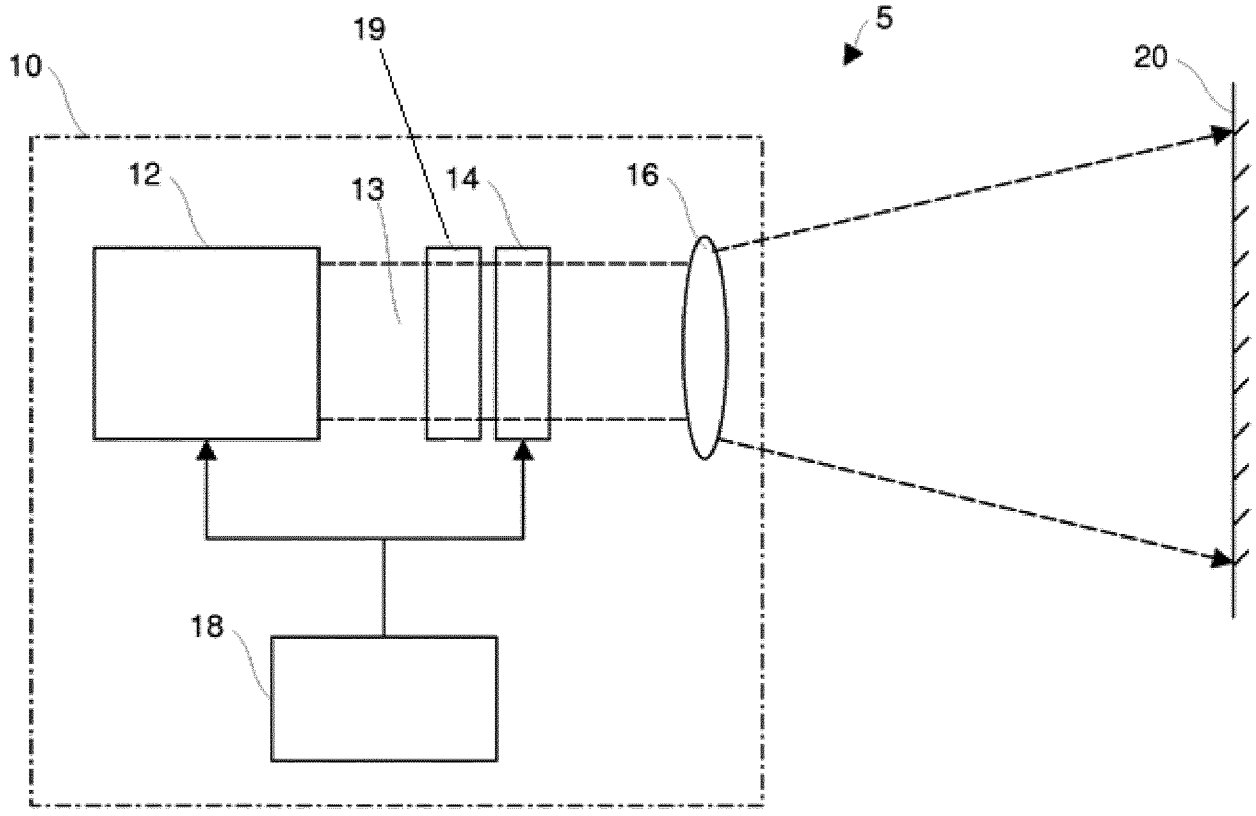


Fig. 2

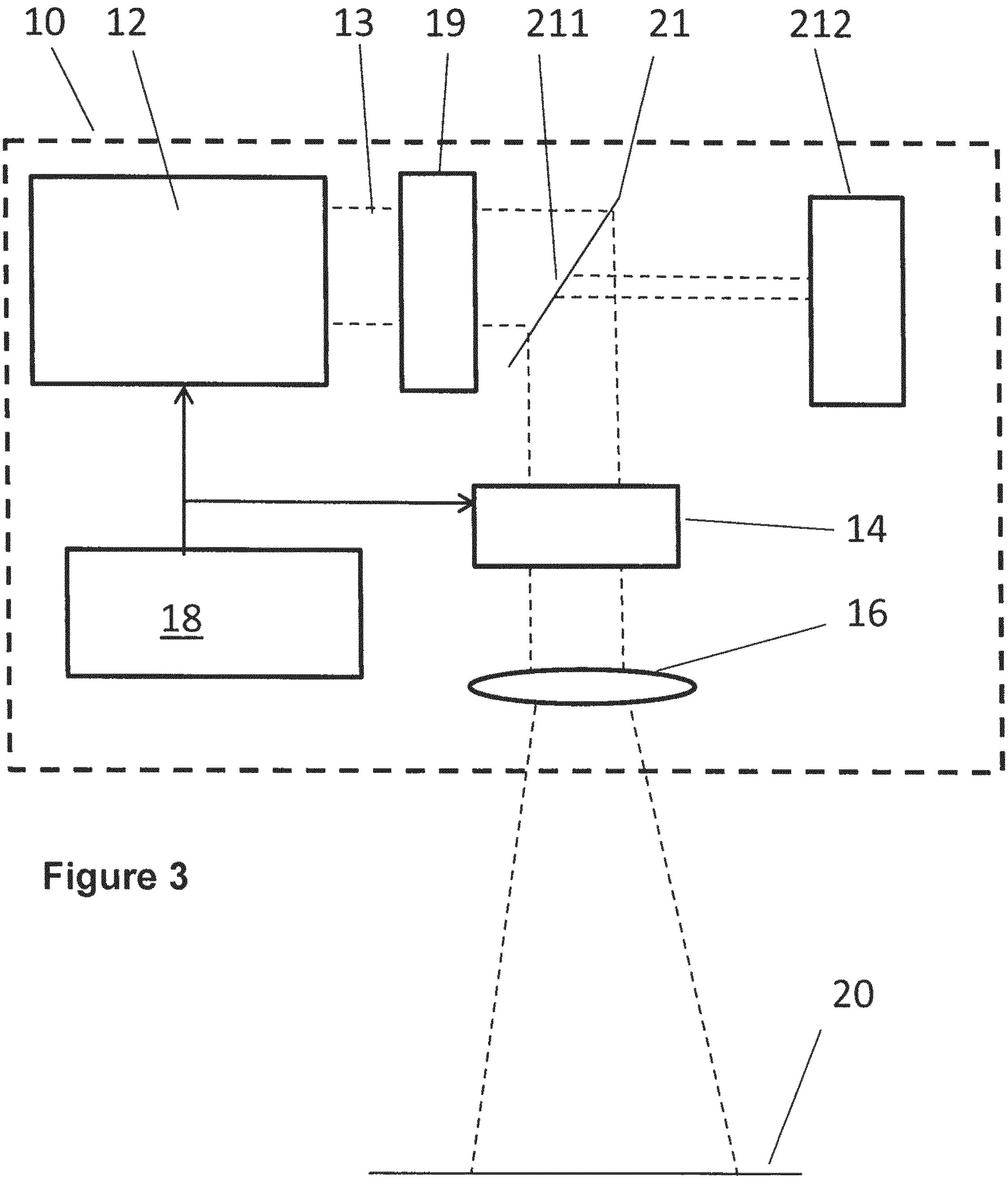
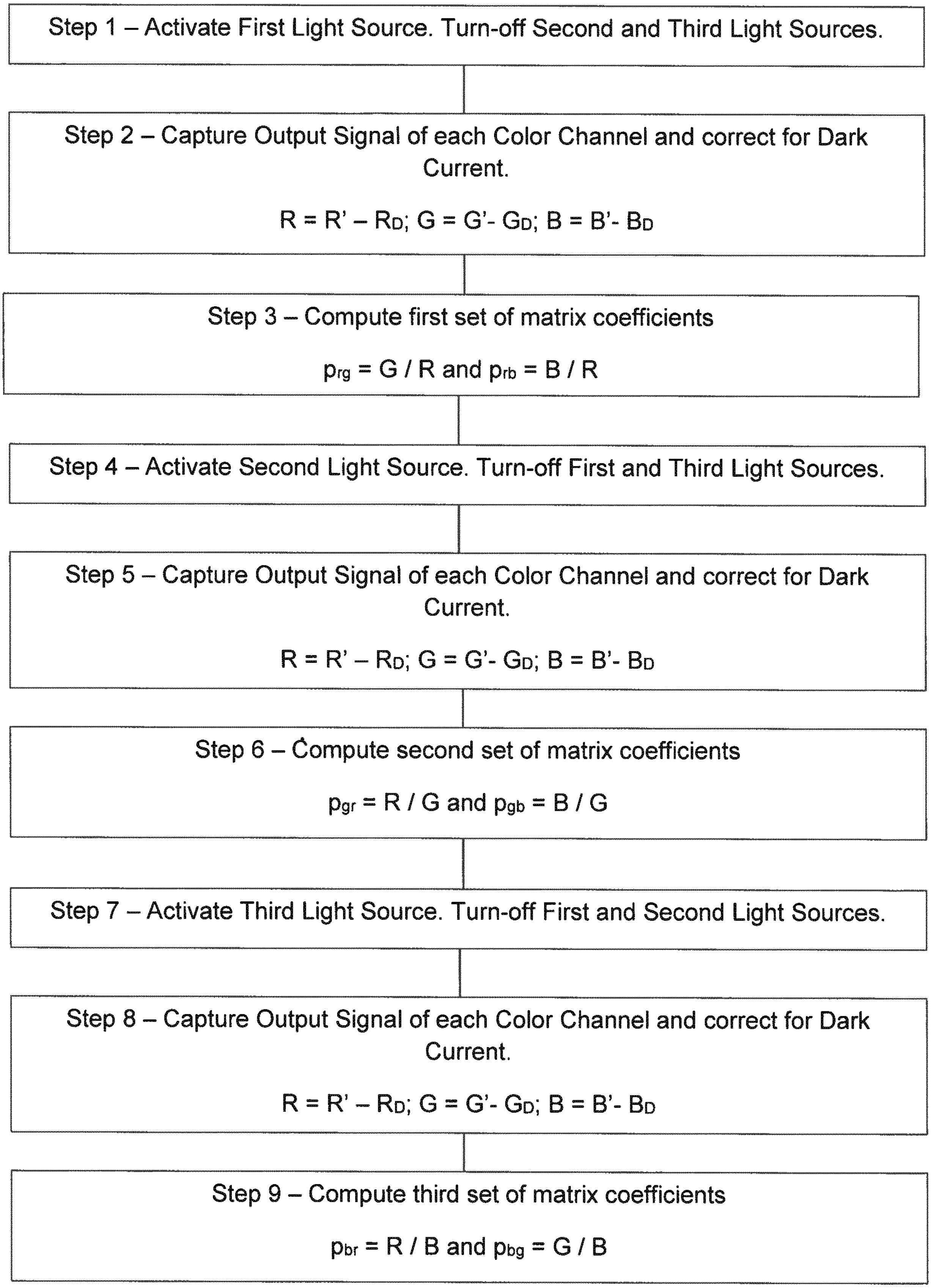


Figure 3

Figure 4



Step 1 – Activate First Light Source. Turn-off Second and Third Light Sources.

Step 2 – Capture Output Signal of each Color Channel and correct for Dark Current.

$R = R' - R_D; G = G' - G_D; B = B' - B_D$

Step 3 – Compute first set of matrix coefficients

$p_{rg} = G / R$ and $p_{rb} = B / R$

Step 4 – Activate Second Light Source. Turn-off First and Third Light Sources.

Step 5 – Capture Output Signal of each Color Channel and correct for Dark Current.

$R = R' - R_D; G = G' - G_D; B = B' - B_D$

Step 6 – Compute second set of matrix coefficients

$p_{gr} = R / G$ and $p_{gb} = B / G$

Step 7 – Activate Third Light Source. Turn-off First and Second Light Sources.

Step 8 – Capture Output Signal of each Color Channel and correct for Dark Current.

$R = R' - R_D; G = G' - G_D; B = B' - B_D$

Step 9 – Compute third set of matrix coefficients

$p_{br} = R / B$ and $p_{bg} = G / B$

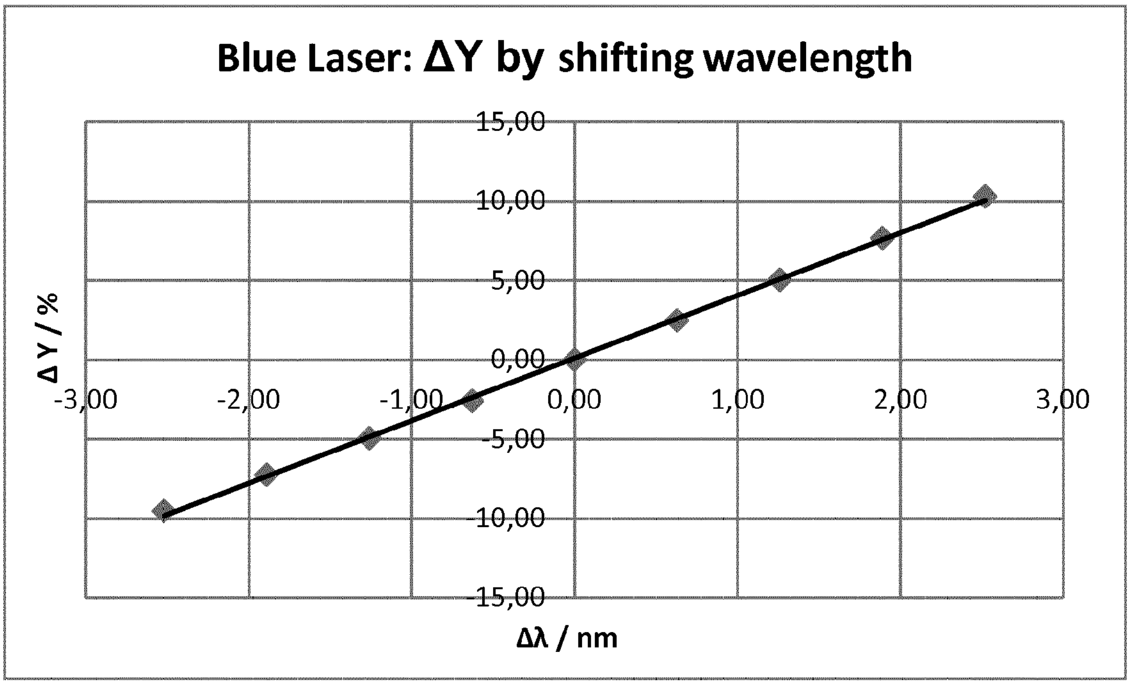


Figure 5

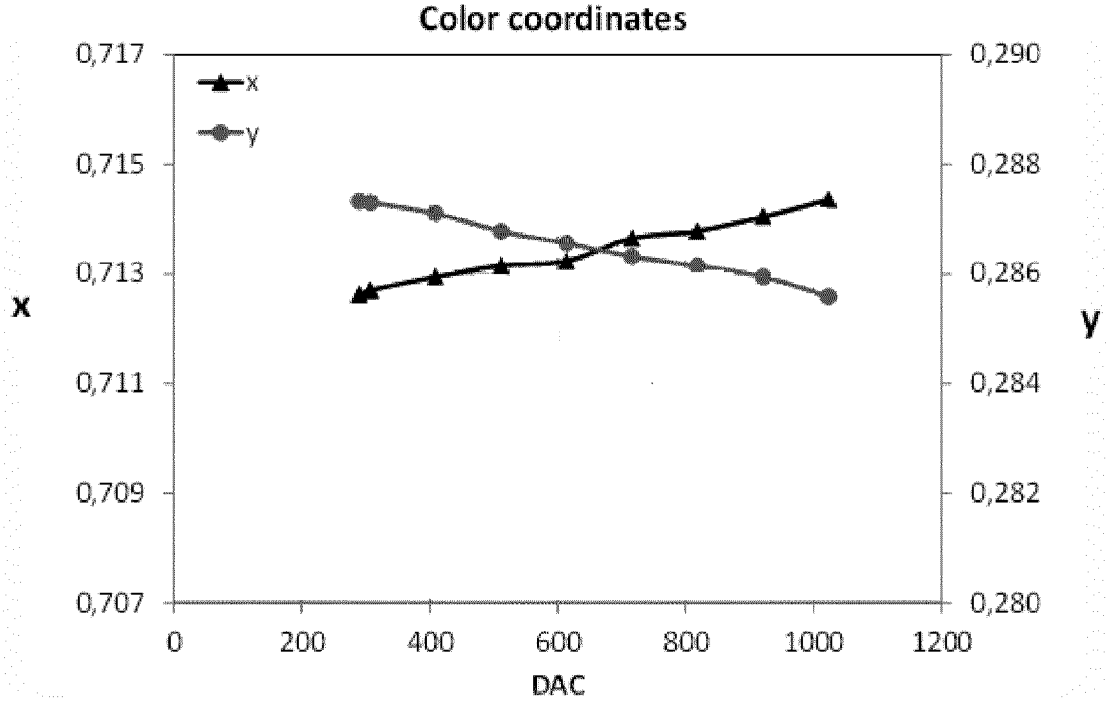


Figure 6

Figure 7A

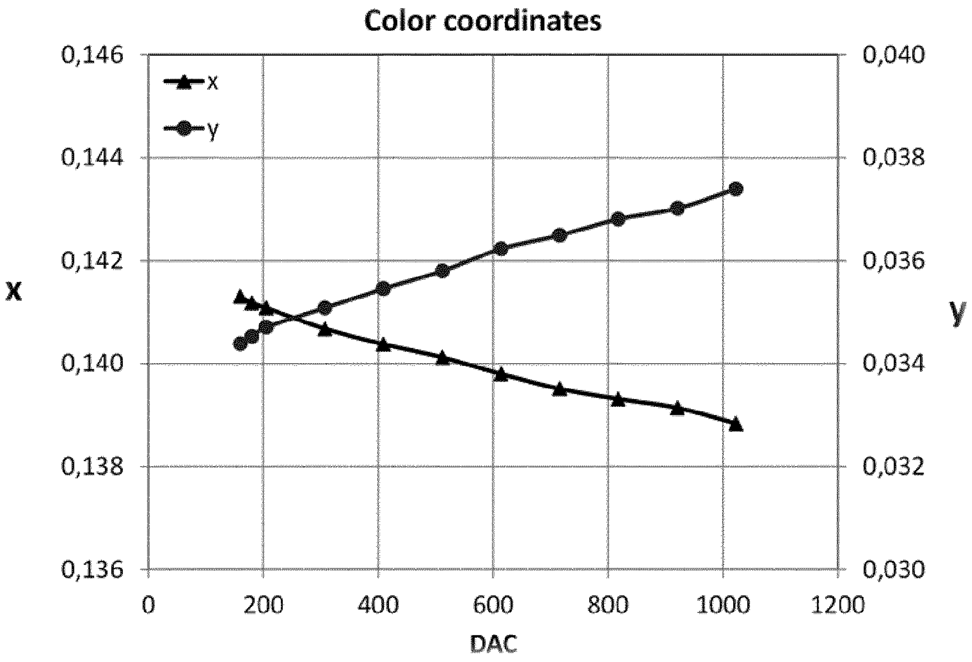


Figure 7B