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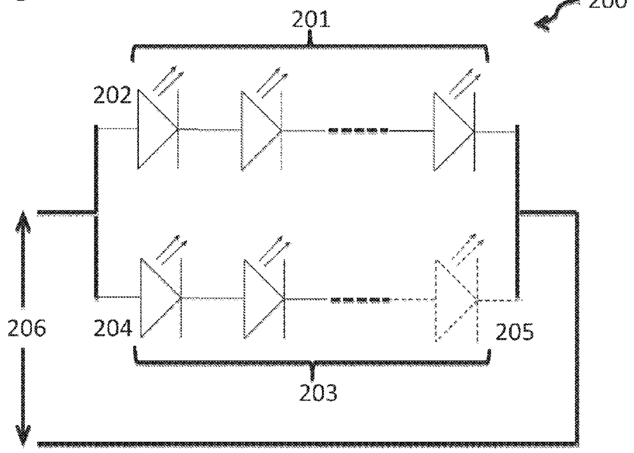
(54) **Title**: LED LIGHT SOURCE WITH PASSIVE CHROMATICITY TUNING

Fig. 2A



(57) **Abstract**: A light emitting module employs non-identical, unmatched devices in two device strings electrically connected in parallel to provides the ability to passively modify the resultant optical properties of the light emitting module, such as chromaticity and luminance, by simple changes in the electrical activation of the overall light emitting module. Each string comprises at least one electrical device, including at least one light emitting device. The electrical devices are selected such that the ratio of their respective luminous flux and the non-zero difference between their effective resistances varies with amount of electrical activation. Also, the chromaticity point of each string is different and the colour chromaticity point of the module varies with amount of electrical activation, such as a constant current supplied to the light emitting module. No complex active electrical regulation, monitoring or feedback to the individual strings of LEDs is required.

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LED Light Source with Passive Chromaticity Tuning

Field of the Invention

The present invention relates to an LED light source, and in particular to an LED light source with passive chromaticity tuning.

Background of the Invention

Light emitting devices and diodes are based on a forward biased p-n junction. LEDs have recently reached high brightness levels that have allowed them to enter into new solid state lighting applications, as well as replacements for high brightness light sources such as light engines for projectors and automotive car headlights. These markets have also been enabled by the economical gains achieved through the high efficiencies of LEDs, as well as reliability, long lifetime and environmental benefits. These gains have been partly achieved by use of LEDs that are capable of being driven at high currents, and hence producing high luminous outputs while still maintaining high wall plug efficiencies.

Light emitting modules comprising arrays of multiple light emitting diodes (LEDs) are regularly employed in lighting grade LED modules and are known in the art, as described in US5032960. Such modules comprise arrays of multiple LED chips mounted on the same substrate or LED modules, comprising LED chip and substrate, electrically connected together. The total radiated light from a light emitting module will comprise a summation of contributions from the individual LEDs.

It is also known in the art that multiple strings of LEDs can be arranged in multiple series and parallel wiring configurations to form stable light sources having stable chromaticity, luminance and electrical properties that can be powered by a single electrical activation source, such as described in GB2458972.

More recently, light emitting modules have been further arranged in bridge configurations to enable electrical activation using a.c. power. Some prior art examples are described in US4298869, US4329625 and US7956367.

It is often an object of known configurations to create strings of LEDs that are balanced in forward voltage so that during electrical activation all of the LEDs in the light emitting module or array are powered at identical constant current values in order to achieve consistent electrical and optical characteristics over their lifetime.

In a typical example, as shown in Figure 1, the light emitting module, 100, has two strings of equal numbers of LEDs, 101 and 103, each having similary matched forward voltages (at the particular desired operating current) and electrically activated using one constant current power supply, 105. During operation, a constant current 105 is supplied, which is set at twice the current supplied into each represetative LED, 102 and 104, of each string. The matched voltages on each string of LEDs, namely 101 and 103, ensures that a balanced current is equally divided between the 2 strings. This provides several benefits as will be outlined below.

Firstly, the total voltage of each LED string is half the total forward voltage of the all the devices if arranged in series, thereby ensuring simpified power supply requirements.

Secondly, during prolonged electrical activation, the matched performance of the LEDs ensure all the operating junction temperatures for all the light emitting diodes are closely matched, ensuring all LEDs are emitting matched luminous flux and that the luminous flux degradation with time for all LEDs is similarly matched across both strings for improved lifetime stability and characteristics.

Thirdly, the matched characteristics of all the LEDs ensures that during operation any changes in ambient temperature or electrical drive characteristics are evenly divided between each parallel string and so there are no imbalances in the current to the strings. Such imbalances are avoided in order to eliminate situations where thermal runaway may occur.

Consider the situation where the voltage across one of the parallel strings, for example 103, is lower than that across string 101. Due to the inbalance, more current is provided into string 103. As a consequence of this increase in current, the LED junction temperature will increase leading to a drop in the forward voltage of the device. This is turn will further increase the current supplied to string 103 as the total voltage across string 103 is reduced. The light emitting module may no longer be able to sustain a stable mode of operation and the recursive nature may lead to string 103 being supplied 80% of the total input current, leading to dramatically accelerated ageing of LEDs in string 103 as compared to string 101.

As will be appreciated by those skilled in the art, there is currently a need for a light emitting module having the optical and electrical stability properties of known modules, but at the same providing a simple and low cost design for tunable colour chromaticity.

Summary of the Invention

According to the present invention there is provided a light emitting module having a light emission spectrum characterised by a module colour chromaticity point and luminous flux, the module comprising:

a first device string comprising **m** devices electrically connected in series, including **p** light emitting devices, wherein **m** and **p** are integers such that **m** ≥ **p** and **p** ≥ 1, and wherein upon electrical activation the first device string has a first effective resistance equal to the summation of the instantaneous voltage to current ratios across each device in the first device string and has a first light emission spectrum characterised by a first chromaticity point and a first luminance;

a second device string comprising **n** devices electrically connected in series, including **q** light emitting devices, wherein **n** and **q** are integers such that **n** ≥ **q** and **q** ≥ 1, and wherein upon electrical activation the second device string has a second effective resistance equal to the summation of the instantaneous voltage to current ratios across each device in the second device string and has a second light emission spectrum characterised by a second chromaticity point and a second luminance; and,

means for electrical activation of the light emitting module,

wherein the first device string and the second device string are electrically connected in parallel and colour chromaticity of light from the module is determined by an additive colour summation of light from the first and second device strings, and

wherein devices in the first and second device strings are selected such that:

the difference between the first and the second effective resistance is non-zero and varies with amount of electrical activation,

the first chromaticity point is different than the second chromaticity point;

the ratio of the first and second luminous flux varies with amount of electrical activation of the light emitting module; and,

the module colour chromaticity point varies with amount of electrical activation of the light emitting module.

It is an object of the present invention that the LEDs in each string are selected to have non-matching electrical and optical properties, yet still provide all the benefits of known modules in terms of optical and electrical stability properties. The light emission spectrum of the first device string is characterised by a different dominant wavelength than the light emission spectrum of the first device string.

By employing non-identical, unmatched devices in the two device strings, the present invention provides the ability to passively modify the resultant optical properties of the light emitting module, such as chromaticity and luminance, by simple changes in the electrical activation of the overall light emitting module. These changes may include variations in constant current supplied to the complete light emitting module, but without the need to introduce complex active electrical regulation, monitoring or feedback to individual strings of LEDs.

In some embodiments **m** > **n**, such that there are more devices in the first device string than in the second device string, rather than there being equal numbers of devices in the two strings

In one preferred embodiment **m** = **p**, such that all of the devices in the first device string are light emitting devices. Likewise, in some preferred embodiments, **n** = **q**, such that all of the devices in the second device string are light emitting devices. Although the minimum number of light emitting devices in each string is one, there will typically be several such devices, carefully selected to provide the desired passive tuning characteristics.

Alternatively, when **m** > **p,** the first device string may comprise (**m**-**p**) non-light emitting devices. Likewise, when **n** > **q**, the second device string may comprise (**n**-**q**) non-light emitting devices. The non-light emitting electronic devices may comprise one or more of a diode, resistor, integrated circuit, transistor, and operational-amplifier. Of course, other types of electrical or electronic component are possible.

In some embodiments, the second effective resistance is greater than the first effective resistance. This can help improve thermal de-rate and avoid runaway of current on the modules.

In a preferred embodiment the first device string includes a first type of light emitting device, and the second device string includes at least one light emitting device of a second type, wherein, upon electrical activation, the effective resistance, colour chromaticity and luminance of the first type of light emitting device is different than the respective effective resistance, colour chromaticity and luminance of the second type of light emitting device.

The second device string may further include at least one light emitting device of the first type. Additionally, or alternatively, the second device string may include at least one light emitting device of a third type, wherein, upon electrical activation, the effective resistance, colour chromaticity and luminance of the third type of light emitting device is different than the respective effective resistance, colour chromaticity and luminance of the first and second types of light emitting device.

Preferably, the difference in effective resistance of the first and second type of light emitting device is at least 15%.

In some embodiments the light emitting device of the first type comprises an LED with a wavelength converting material and the light emitting device of the second type comprises a monochromatic LED. The second type of light emitting device may have a dominant wavelength selected from Red, Amber, Red-Orange, Green, and Blue.

The different light emitting devices may comprise different material systems, different dopants or doping levels, different quantum wells or heterojunctions, or combinations thereof.

In one implementation of the present invention, the electrical activation means comprises an adjustable source of constant electrical current. In a particularly preferred embodiment, the light emission spectrum of the module exhibits a shift in colour chromaticity point of greater than 3 MacAdam ellipses and in the direction of the first or second colour chromaticity point when the activating constant electrical current is changed by at least 10%.

In some embodiments, the light emitting module may further comprises a third device string electrically connected in parallel with the first and second device strings, the third device string comprising devices electrically connected in series, including at least one light emitting device, wherein upon electrical activation the third device string has a third effective resistance equal to the summation of the instantaneous voltage to current ratios across each device in the third device string and has a third light emission spectrum characterised by a third chromaticity point and a third luminance which vary with amount of electrical activation of the light emitting module.

The use of a third parallel device string allows for even more combinations of devices and passive chromaticity tuning characteristics. Of course, the concept can be extended further to four or more parallel strings of devices, each made up of matched and unmatched devices carefully selected to achieve the desired chromaticity and passive tuning.

As will be appreciated by those skilled in the art, the approach adopted in the present invention for the construction of a light emitting module is somewhat contrary to that used in known modules. However, the resulting light emitting module can exhibit desirable passive chromaticity tuning characteristics whilst still providing the benefits of known modules in terms of optical and electrical stability properties.

Brief Description of the Drawings

Examples of the present invention will now be described in detail with reference to the accompanying drawings, in which:

Figure 1A shows a known LED module with two parallel strings of LEDs;

Figure 2A shows a schematic of an example light emitting module of the present invention;

Figure 2B shows forward voltage against current of representative LED devices of type 202 and 205;

Figure 2C shows the current injected into string 201 and 203 against the total current injected into the light emitting module 221;

Figure 2D shows the ratio between the current provided into string 201 and 203;

Figure 2E shows a 1931 CIE chromaticity chart indicating the colour points for LED 243, 244 and 247 as well as the chromaticity colour shift of the light emitting module of Figure 2A;

Figure 2F shows a rescaled 1931 CIE chromaticity region indicating the colour points for LED 243, 244 and 247 as well as the chromaticity colour shift of the light emitting module of Figure 2A;

Figure 3A shows the instantaneous resistance of an LED type 202 and 205 plotted against the input current;

Figure 3B shows a representative equivalent schematic of the light emitting module of the present invention using resistors;

Figure 4 shows another example of a light emitting module of the current invention having a further diode;

Figure 5 shows a light emitting module of the current invention comprising of an LED chip on board design;

Figure 6A shows a schematic of a further example of a light emitting module of the present invention having a four blue and WCE LED on string 601 and two Green LEDs, two Red LEDs and a further blue and WCE LED on string 603;

Figure 6B shows a 1931 CIE chromaticity chart indicating the chromaticity colour shift of the light emitting module shown in Figure 6A;

Figure 7A shows a schematic of a further example of a light emitting module of the present invention having three blue and WCE LED and one Red LED on string 601, and two Green LEDs, two Red LEDs and a further blue and WCE LED on string 603; and,

Figure 7B shows a 1931 CIE chromaticity chart indicating the chromaticity colour shift of the light emitting module shown in Figure 7A.

Detailed Description

As shown in Figure 2A, an example light emitting module (LEM) 200 of the present invention comprises two light emitting device (LED) strings, 201 and 203, connected in parallel. The light emitting module is electrically activated using constant current through 206. The first string, 201, and second string, 203, comprise of a series arrangement of light emitting devices, 202, 204 and 205.

The LED may comprise of a semiconductor light emitting diode or an organic light emitting diode or other light emitting materials. The LED may further comprise a wavelength converting element (WCE) material. The WCE converts the light emitting diode from a monochromatic device to a polychromatic device, having additive colour contribution from the underlying light emitting diode and the WCE emission.

The wavelength converting element (WCE) may comprise a phosphor, Quantum Dots (QDs), nano-phosphors, organic light emitting material or other electrically, ionically or optically-pumped light emitting material. The wavelength converting elements may further include surface treatments, and WCE shell coatings, to provide improved light coupling and extraction as well as prolong lifetime and thermal stability. The WCE may further comprise optical scatterers or diffusers, as well as refractive index modifying fillers.

The present invention can be implemented using light emitting diodes of any semiconductor material system such as, but not restricted to, GaN, InGaN, InGaP, InGaAlP, InGaAs, InGaAs, InGaP, AlGaP, InAlP, InGaAlN, InP, or ZnO. However, for illustrative purposes, and as a preferred example, the use of Blue and Green wavelength InGaN semiconductor light emitting diode and Red wavelength InGaAlP semiconductor light emitting diode all having vertical contact pad structure (sometimes termed vertical LED structure, or thin GaN) will be described in much of the following.

Electrical activation of a light emitting device may comprise electrically connecting the light emitting devices using voltage or current driven power supplies. The device may be activated using pulsed, switched, sinusoidal, modulated or constant signals. For the purpose of the present invention, the light emitting module is preferably activated using constant current.

For the purpose of describing the present invention, the colour chromaticity will be defined with reference to a 1931 CIE Chromaticity Diagram using a CIE xyY colour space, defining CIE xy as colour chromaticity and CIE Y as the luminance. A standard 1931 CIE Chromaticity colour space diagram is shown in Figure 2E. For simplicity, the luminance parameter will be separated from the notation and only the chromaticity parameters will be specified by the parameters ***x,y*** on the colour space.

LED 202 and 204 comprise blue monochromatic light emitting diodes having a WCE. In a first example of the present invention, LED 202 and 204 have a warm white correlated colour temperature (CCT) of approximately 3000K. String 201 comprises four LEDs of type 202, and string 203 contains four LEDs of type 204. String 203 further contains one LED of type 205, having a monochromatic Red dominant emission wavelength. It is noted that type 205 LED is of a different semiconductor material system (namely InGaAlP), and therefore exhibits lower forward voltage properties at the same current injection as compared with an LED of type 202 and 204.

Figure 2B shows the forward voltage (210) characteristics against current injection (in A) for each LED (211). The white LED of type 202 and 204 are shown in dashed line 213, whereas the solid line 212 identifies a Red LED of type 205. The forward voltage for LED 202 and 204 is approximately 3.0V at 350mA (a typical recommended operating current for power LEDs) and for the Red LED 205 a forward voltage of approximately 2.1V at 350mA is typically measured. The resultant total forward voltage for string 203 is greater than string 201.

When electrical current is input into the light emitting module through 206, the imbalance in the forward voltage of string 201 and 203 causes the current to be fed in different proportions into each string. A typical example is shown in Figure 2C, where the current (in mA) into the light emitting module, 221, is plotted against the current in each string, 220. In an example of the prior art, and by way of a theoretical reference situation, if string 201 and 203 are matched and the total forward voltage of all the LEDs in the string are balanced, then the current into each string will be equally divided. This situation is indicated in Figure 2C by the dotted line 224. By contrast, in the example of the present invention, string 201, having a lower total forward voltage, experiences an increased overall current bias, as shown at 223. This is in contrast to string 203, which has one more LED and therefore an increased overall forward voltage resulting in a reduced current bias, 222. It is important to note that the total current into any string cannot exceed the input current.

It is an object of the present invention that, as the current 230 into the light emitting module (I_{module} in mA) changes, the ratio between the current provided into string 201 and 203 varies. This variation is plotted in Figure 2D, which shows the ratio of the actual current injection into each string when compared to the current flowing in a string of a reference balanced light emitting module. The current of the reference balanced light emitting module is $I_{module}/2$. The ratio for string 1, plotted as 234, and for string 2, plotted as 233, is calculated using the following expressions:

$$ratio_{234} = \frac{I_{string\ 201}}{I_{module}/2} \tag{1}$$

$$ratio_{233} = \frac{I_{string\ 203}}{I_{module}/2} \tag{2}$$

where $I_{string\ 201}$ and $I_{string\ 203}$ is the actual current injected into each string and I_{module} is the current into the overall light emitting module. As illustarted in Figure 2D, axis 231 highlights the change in ratio for string 203 and axis 232 highlights the change in ratio for string 201. It is an object of the present invention that, as the current increases, the ratio of current injected into string 2 decreases while the ratio of current injected into string 1 increases.

The LEDs residing within the light emitting module are selected so that the maximum current injection into any LED never exceeds the maximum rating of the device. This is determined by calculating the actual current in each string at all allowed light emitting currents and temperatures. This ensures that the LEDs do not operate outside the recommended operating current and temperature and ensures electrical stability of the system. It is important to the note that, in a typical LED device, the forward voltage of the LED decreases with increasing junction temperature.

The present invention further provides the ability to passively modify the resultant optical properties of the light emitting module, such as chromaticity and luminance, by changes in the electrical activation of the overall light emitting module. At least one of chromaticity or luminance for each string in the light emitting module is different. In the example shown in Figure 2E, the chromaticity point for the individual LEDs, 202, 204 and 205, are indicated by the black crosses 243, 244 and 247, respectively. The summed chromaticity point for string 201 is shown at 243 and for string 203 at 249. These are warm white correlated colour temperatures (CCT) of approximately 3000K, with the cross denoted at 244 residing off the black body locus (depicted by line joining the diamond markers) and in the direction of green. In order for LED 244 to deliver a white colour residing on the black body locus, the Red LED residing on chromaticity point 247 shifts the total summed string 204 chromaticity to point 249. This is depicted in an expanded view in Figure 2F. The solid triangle bounded by 243, 244 and 247, defines the individual chromaticity point boundaries of the LEDs 202, 204 and 205.

During electrical activation the light emitting module can theoretically achieve chromaticity points bounded by point 243 and 249, assuming that the relative current bias in string 201 and 203 can shift from 0 to 100% between the two strings (also assuming one of the strings can achieve an inifinite forward voltage). In practice, the current in string 201 and 203 is always finite and both strings are always activated. Using additive colour summation theory the chromaticity points of the total light emitting module will lie between point 245 and 246. It is important to note that the absolute location of 245 and 246 will also be determined by the luminance of the individual LEDs within each string. This can be determined by the following equations:

$$x_3 = \frac{Y_1}{Y_1 + Y_2} x_1 + \frac{Y_2}{Y_1 + Y_2} x_2 \quad (3)$$

$$y_3 = \frac{Y_1}{Y_1 + Y_2} y_1 + \frac{Y_2}{Y_1 + Y_2} y_2 \quad (4)$$

where (x_1, y_1, Y_1) and (x_2,y_2,Y_2) define the chromaticity point and luminance for first and second light source, respectively, and (x_3,y_3,Y_3) defines the chromaticity and luminance of the (third) resultant colour mixed light source.

During operation the constant current supplied to the light emitting module can change as a result of an operation such as dimming the light source. As an example, the current may decrease from 1000mA to 175mA. Due to the changes in the relative current in each string, the relative luminance supplied by each string varies, and hence the chromaticity point of the light emitting module vaires. In the present example, at 1000mA the module chromaticity resides at point 245 and shifts in the direction of the arrow 248 to chromaticity point 246 when the current is dimmed to 175mA. This example achieves a white colour tunable source, since the colour tunable source shifts to a lower CCT as the current is reduced.

In another aspect of the present invention the chromaticity shift is closely matched to shifts in black body radiation sources, such as incandescent lamps and halogen lamps. This provides for incandescent and tungsten lamp CCT emulation, characterised in that dimming such lamps shifts the colour temperature from approximately 3000K to approximately 2400K.

In a further aspect of the present invention, the introduction of a long wavelength saturated colour, having a dominant wavelength in the Red or Orange region of the spectrum, provides further improvements in the colour rendering index (CRI) of the total emitted light of the light emitting module.

In another aspect of the invention the light emitting module is not confined to white colour tuning. It is an object of the current invention to define a chromaticity tunable source by varying the input current to the light emitting module.

In a further advantage of the present invention the light emitting module provides chromaticity tunability without the need to introduce complex active electrical regulation, monitoring, electrical or optical feedback to individual strings of LEDs or the light emitting module.

Electrical activation of the light emitting module can be, but not limited to, constant voltage, constant current (I_{in} as indicated in Figure 3B) or a modulation of the input electrical waveform (in the form of pulses or waveforms having regular or irregular characteristics).

In order to determine the current injected into each string, and how this is shared between the two light emitting strings (I_1 and I_2), Kirchoffs law (Equation 5) and a modified Schockley diode equation (Equation 6) are utilised, as follows:

$$I_{in} = I_1 + I_2 \qquad (5)$$

where ***m*** is the total number of elements in string 301 and ***n*** is the total number of elements in string 303, and

$$R_{inst} = \frac{A_1 \ln\left(\frac{I_{inst}}{A_2} + 1\right)}{I_{inst}} \qquad (6)$$

where,

$A_1 = nV_T$

$A_2 = I_S$

I is the diode current,

I_s is the reverse bias saturation current,

V is the voltage across the LED,

V_T is the thermal voltage,

n is the ideality factor.

Based on the Schockley diode equation the instantaneous resistance of each LED is a function of the instantaneous current supplied to the LED. Figure 2B highlights typical LED characteristics with the forward voltage plotted against electrical activation current. The circuit shown in Figure 2 can be replaced by the equivalent effective R_{inst} resistors, as shown in Figure 3B, at a specific instantaneous electrical activation in order to simplify calculation of the current into each string. An iterative root finding algorithm is employed to determine the actual R_{inst} in each string, since R_{inst} varies nonlinearly with changes in injected current.

The present invention makes use of the non-linear relationship between voltage and current in the LED as well as the difference in the Schockley diode characteristics of different semiconductor materials systems. The use of LEDs from different material systems, such as InGaAlP (for saturated Yellow to Red emission) and InGaN material systems (for the generation of Blue to Green saturated emission and WCE converted white or pastel emission), provides the ability to tune the forward voltage (as shown in Figure 2B) of each string while benefiting from the ability to passively shift chromaticity.

In the case of the first example of the present invention, the total resistance across 301 does not equal the total resistance across 303.

$$\sum_{x=1}^{m} R_{1x}(I_1) \neq \sum_{y=1}^{n} R_{2y}(I_2) \qquad (7)$$

where I_1 and I_2 denote instantaneous current in string 1 and 2, respectively, and $R_{1x}(I_1)$ is the resistance of device number x on string 1 at current I_1 and $R_{2y}(I_2)$ is the resistance of device number y on string 2 at current I_2.

It is also a further aspect of the present invention that the difference in the total effective resistance across 301 and 303 varies with changes in the current input to the light emitting module due to the nonlinear characteristics of the LEDs. Figure 3A shows the instantaneous resistance (R_{inst}) plotted against current (I_1/I_2

in A). The solid line plots the variation in resistor 305, which simulates LED 205, and the dashed line plots the variation in resistor 302, which simulates LED 202. The schematic provides a simplified means of determining the current injected into string 301 and string 303.

In another aspect of the present invention, additional electronic components may reside on string 401 and 403. The elements may comprise devices such as, but not limited to, diodes, current regulation ICs, regulators, resistors or current limiters.

In a preferred example of the invention, a diode, 404, is introduced into one or more of the LED strings as shown in Figure 4A. This can be selected to tailor the forward voltage characteristics of the string in order to enable the desired current to be split between the two strings, yet still provide nonlinear properties.

Figure 5 shows an example light emitting module of the present invention, which comprises a white colour tunable chip-on-board module (COB), 500. Electrical tracking, 505, is disposed on a substrate, 508. The substrate may comprise a top electrically-insulated metal-backed electrical board or ceramic. The vertical type LED devices are arranged in two strings and the LEDs are die bonded or soldered onto contact pads, 509. In other examples, lateral devices may be employed. String 1 employs four blue InGaN based LEDs with WCE disposed on the surface, 503, to form substantially white light emission. String 2 comprises three blue InGaN based LEDs with WCE disposed on the surface, as well as a further two Red InGaAlP based LEDs, 510. The LEDs are wire bonded to form a series arrangement, 504, and string 1 and 2 are connected in parallel through the common anode and cathode, 507 and 506, respectively. Subsequent to die and wire bonding a dam, 501, and encapsulant fill, 502, process is applied around and over the perimeter of the LEDs to protect the LEDs from the environment. In some examples, an optical overmold or optical dome is applied over the light emitting module to further improve the optical extraction and help improve colour mixing.

In another example of the present invention, a high colour quality white tunable light emitting module, 600 is proposed, as shown in Figure 6A. String 601 comprises four blue LEDs with WCE elements, 602, and string 603 comprises two Green InGaN LEDs, 604, two Red InGaAlp LEDs, 605, and a further blue LED with WCE element, 602. The effective forward voltage (as well as effective R_{inst}) of string 603 is greater than string 601 in the recommended operating current range for the exemplary light emitting module (0mA to 1000mA). The use of saturated Red, Green and Blue LED in the light emitting module further provides a high CRI and high colour quality scale (CQS) greater than the individual LEDs within the module and specifically greater than the white LED 602, and a Gamut Area Index (GAI) greater than the individual LEDs within the module, and specifically greater than the white LED 602.

In embodiments of the present invention the CRI is preferably greater than 90, and more preferably greater than 93. In some embodiments the GAI is preferably greater than for an incandescent or halogen lamp.

In a preferred mode of operation the light emitting module 600 is operated at 700mA to achieve the chromaticity point 621 shown in Figure 6B. However, when the current is dimmed down to 50mA, the chromaticity point shifts along the chromaticity shift line 613 to new chromaticity point 622. The chromaticity points of individual LEDs are highlighted as 614 for LED 604, 612 for LED 602 and 615 for LED 605.

As shown in Figure 7A, in a further example of the present invention, a high colour quality white tunable light emitting module having an improved colour recipe, 700, is proposed. String 701 comprises three blue LEDs with WCE elements, 702, and one Red InGaAlP LED, 705. String 703 comprises three blue LEDs with different WCE elements, 704, and two Red InGaAlP LEDs, 705, as well as a further blue LED with WCE element, 602. The effective forward voltage (as well as effective R_{inst}) of string 703 is greater than string 701 in the recommended operating current range (0mA to 1000mA) of the exemplary light emitting module.

The use of saturated Red, 705, and green shifted white LEDs, 702, in the light emitting module provides a high CRI and high colour quality scale (CQS) greater than the individual LEDs within the module, and specifically greater than the white LED 702, and a Gamut Area Index (GAI) greater than the individual LEDs within the module, and specifically greater than the white LED 702.

In a preferred mode of operation the light emitting module 700 is operated at 700mA to achieve a chromaticity point shown at 711 in Figure 7B. When the current is dimmed down to 50mA the chromaticity point shifts to point 712 along the chromaticity shift line 713. The chromaticity points of individual LEDs are highlighted as 714 for LED 705, 715 for LED 702 and 716 for LED 704.

In other embodiments, the light emitting module may comprise more than two strings of LEDs. The strings are designed and balanced as described earlier. This may be advantageous for the design of lower total effective forward voltage light emitting module, whereby the total number of LEDs are divided amongst multiple strings. This may also be advantageous in the distribution of multiple LEDs having different forward voltages.

The present invention is not limited to three or four LEDs having different chromaticity points and luminance. In other embodiments, a 5^{th} or 6^{th} different type of LED may be employed in order to further improve the colour chromaticity shift during dimming of the current to achieve the desired colour tuning effect.

As will be appreciated by those skilled in the art, further variants of the invention are possible, which still employing the key principles of the invention. Combinations of multiple strings with many different types of LED and also other electrical components may be utilised in a light emitting module to achieve a desired passive chromaticity tuning.

CLAIMS

1. A light emitting module having a light emission spectrum characterised by a module colour chromaticity point and luminous flux, the module comprising:

a first device string comprising **m** devices electrically connected in series, including **p** light emitting devices, wherein **m** and **p** are integers such that **m** ≥ **p** and **p** ≥ 1, and wherein upon electrical activation the first device string has a first effective resistance equal to the summation of the instantaneous voltage to current ratios across each device in the first device string and has a first light emission spectrum characterised by a first chromaticity point and a first luminance;

a second device string comprising **n** devices electrically connected in series, including **q** light emitting devices, wherein **n** and **q** are integers such that **n** ≥ **q** and **q** ≥ 1, and wherein upon electrical activation the second device string has a second effective resistance equal to the summation of the instantaneous voltage to current ratios across each device in the second device string and has a second light emission spectrum characterised by a second chromaticity point and a second luminance; and,

means for electrical activation of the light emitting module,

wherein the first device string and the second device string are electrically connected in parallel and colour chromaticity of light from the module is determined by an additive colour summation of light from the first and second device strings, and

wherein devices in the first and second device strings are selected such that:

the difference between the first and the second effective resistance is non-zero and varies with amount of electrical activation,

the first chromaticity point is different than the second chromaticity point;

the ratio of the first and second luminous flux varies with amount of electrical activation of the light emitting module; and,

the module colour chromaticity point varies with amount of electrical activation of the light emitting module.

2. A light emitting module according to claim 1, wherein **m** > **n**.

3. A light emitting module according to claim 1 or claim 2, wherein **m** = **p**.

4. A light emitting module according to claim 2 or claim 3, wherein **n** = **q**.

5. A light emitting module according to claim 1 or claim 2, wherein **m** > **p** and the first device string comprises (**m**-**p**) non-light emitting devices.

6. A light emitting module according to claim 5, wherein **n** > **q** and the second device string comprises (**n**-**q**) non-light emitting devices.

7. A light emitting module according to claim 5 or claim 6, wherein the non-light emitting electronic devices comprise one or more of a diode, resistor, integrated circuit, transistor, and operational-amplifier.

8. A light emitting module according to any preceding claim, wherein the second effective resistance is greater than the first effective resistance.

9. A light emitting module according to any preceding claim, wherein:

the first device string includes a first type of light emitting device; and,

the second device string includes at least one light emitting device of a second type,

wherein, upon electrical activation, the effective resistance, colour chromaticity and luminance of the first type of light emitting device is different than the respective effective resistance, colour chromaticity and luminance of the second type of light emitting device.

10. A light emitting module according to claim 9, wherein the second device string includes at least one light emitting device of the first type.

11. A light emitting module according to claim 9 or claim 10, wherein

the second device string includes at least one light emitting device of a third type,

wherein, upon electrical activation, the effective resistance, colour chromaticity and luminance of the third type of light emitting device is different than the respective effective resistance, colour chromaticity and luminance of the first and second types of light emitting device.

12. A light emitting module according to any one of claims 9 to 11, wherein the difference in effective resistance of the first and second type of light emitting device is at least 15%.

13. A light emitting module according to any of claims 9 to 12, wherein the light emitting device of the first type comprises an LED with a wavelength converting material and the light emitting device of the second type comprises a monochromatic LED.

14. A light emitting module according to any of claims 9 to 13, wherein the second type of light emitting device has a dominant wavelength selected from Red, Amber, Red-Orange, Green, and Blue.

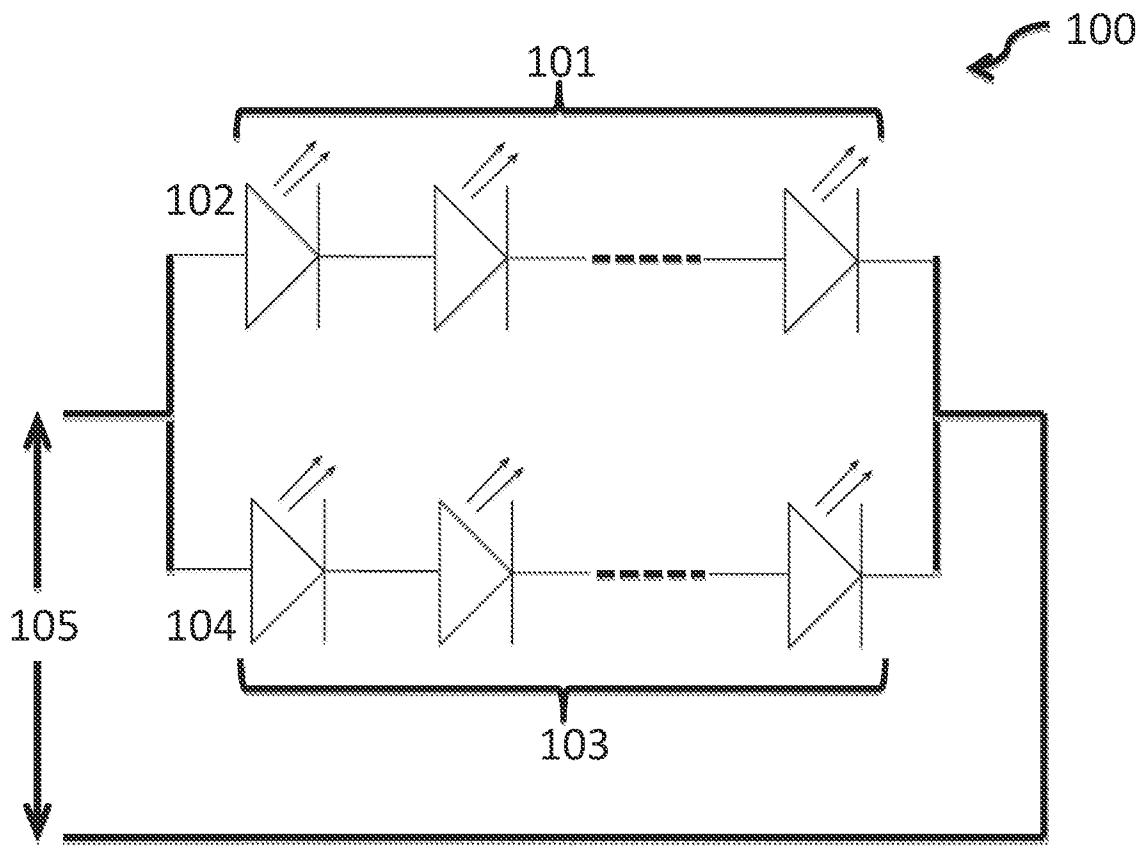
15. A light emitting module according to any preceding claim, wherein the electrical activation means comprises an adjustable source of constant electrical current.

16. A light emitting module according to claim 15, wherein the light emission spectrum of the module exhibits a shift in colour chromaticity point of greater than 3 MacAdam ellipses and in the direction of the first or second colour chromaticity point when the activating constant electrical current is changed by at least 10%.

17. A light emitting module according to any preceding claim, further comprising a third device string electrically connected in parallel with the first and second device strings, the third device string comprising devices electrically connected in series, including at least one light emitting device, wherein upon electrical activation the third device string has a third effective resistance equal to the summation of the instantaneous voltage to current ratios across each device in the third device string and has a third light emission spectrum characterised by a third chromaticity point and a third luminance which vary with amount of electrical activation of the light emitting module.

18. A light emitting module as described hereinbefore.

19. A light emitting module as described hereinbefore with reference to the accompanying drawings.



(Prior Art)

Fig. 1

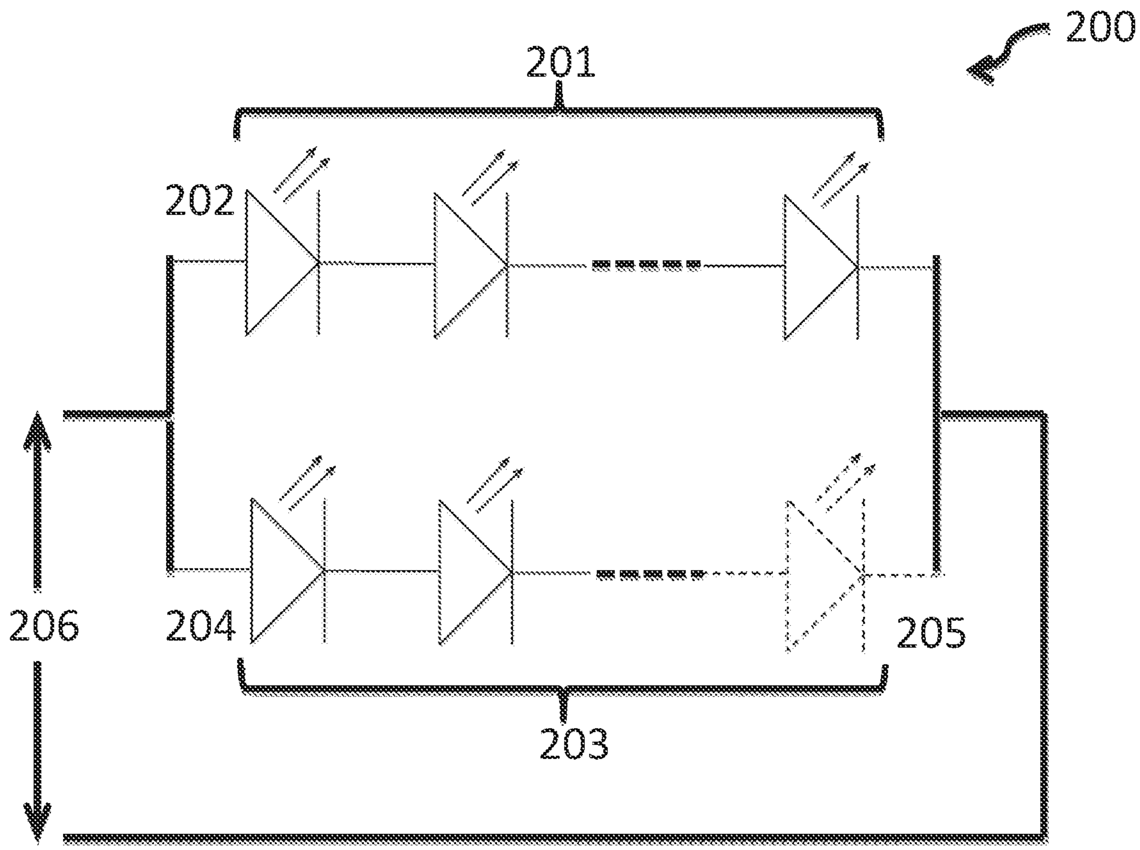
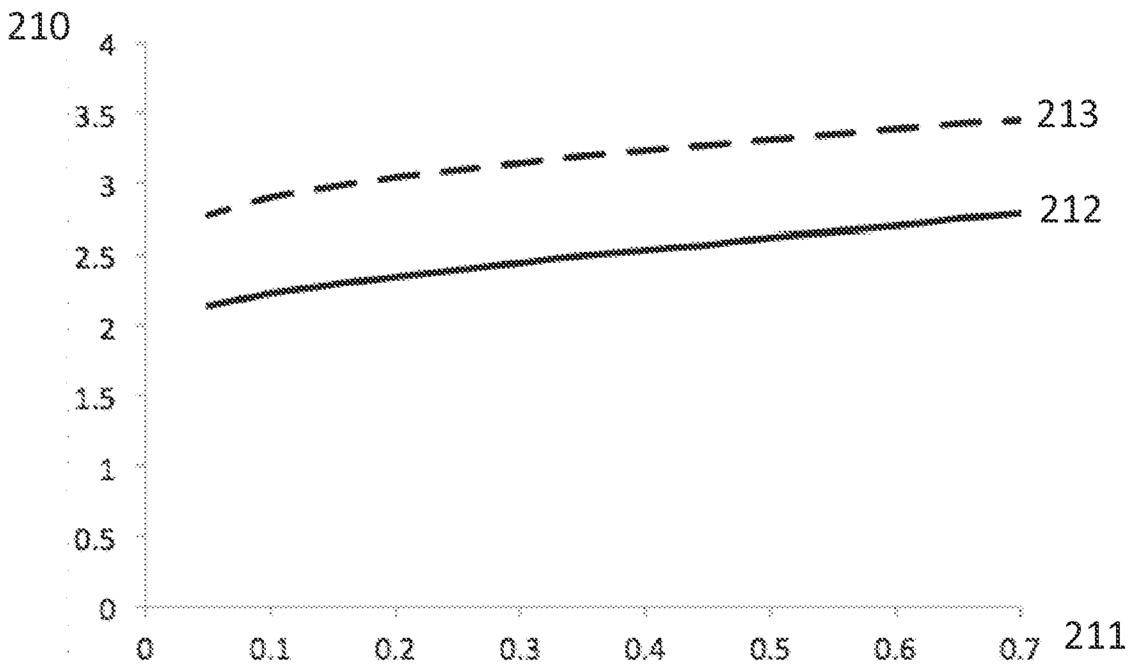


Fig. 2A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2
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1
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0.3
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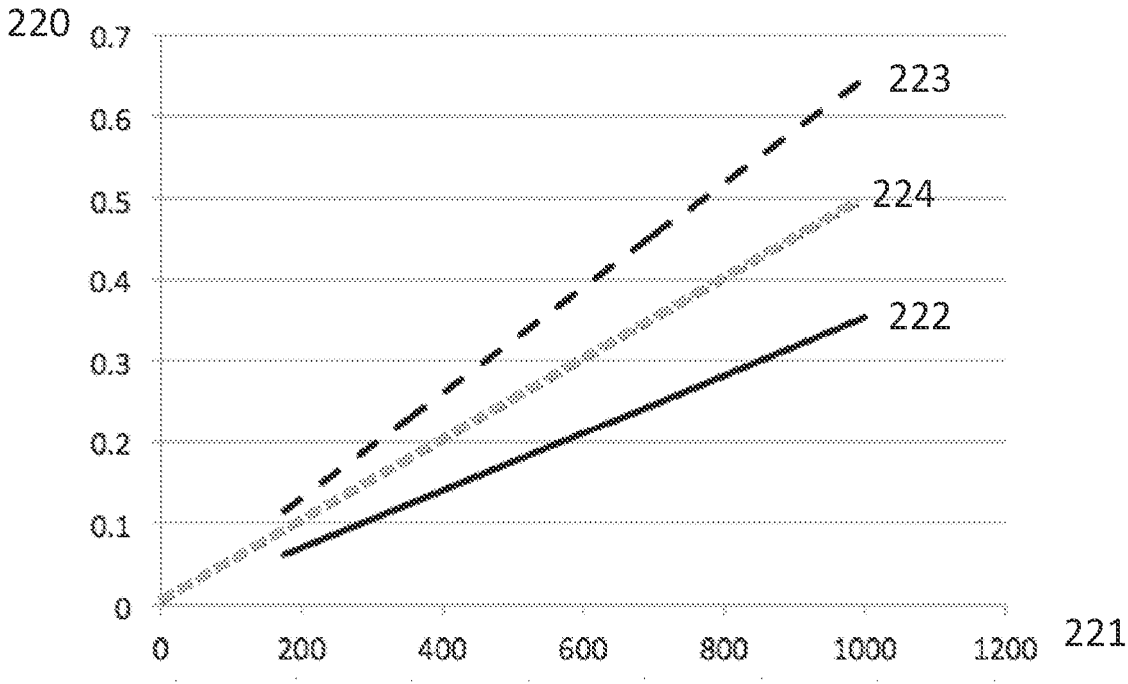
0.6
0.7
211
213
212

Fig. 2B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800
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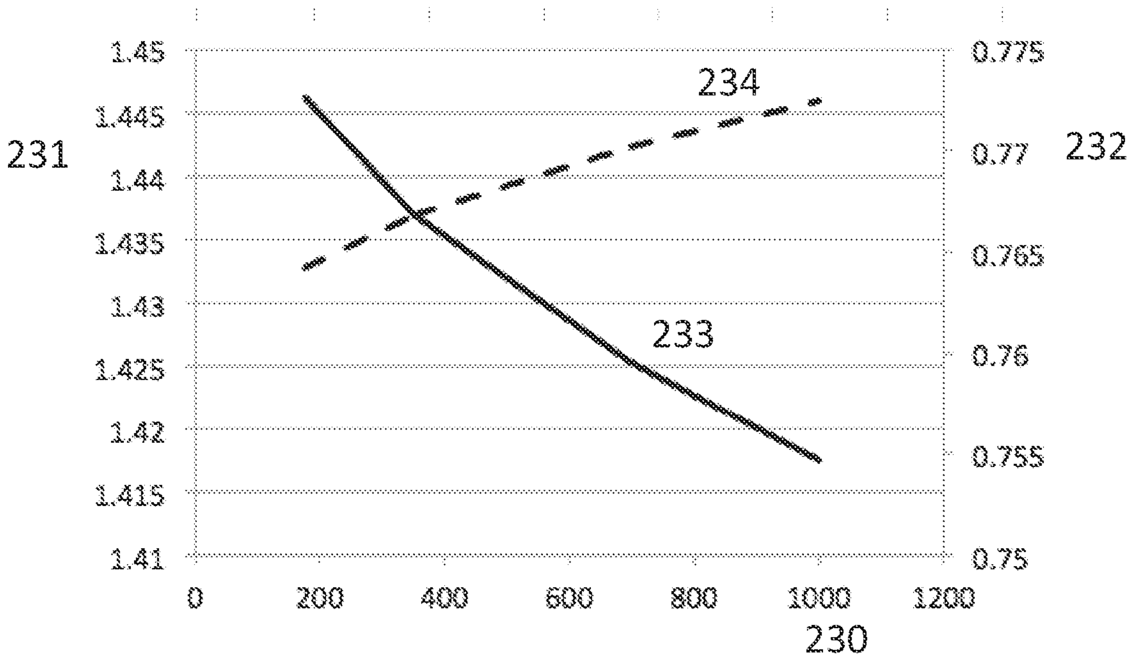
1200
221
223
224
222

Fig. 2C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400
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1000
1200
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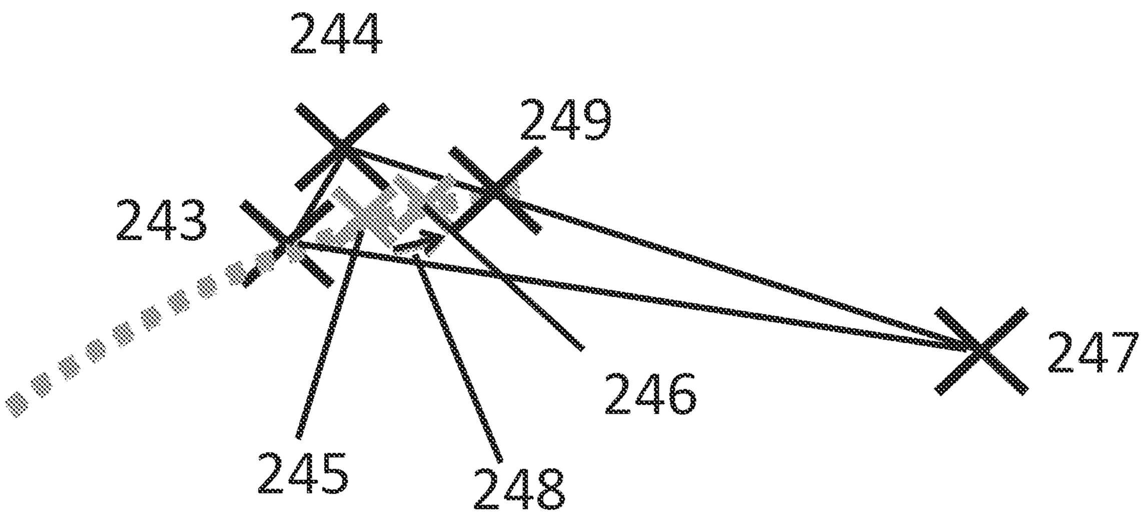
232
233
234
230

Fig. 2D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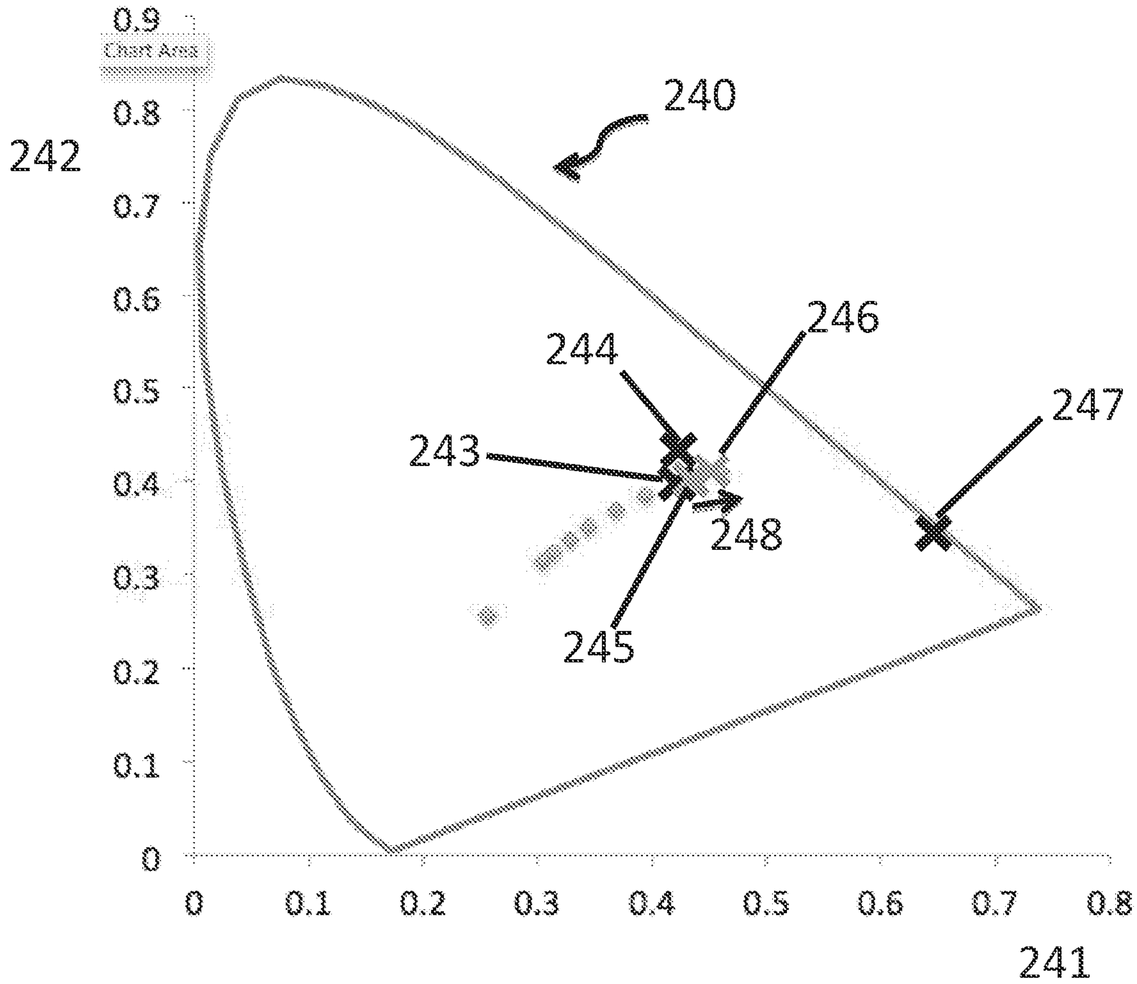
248

Fig. 2F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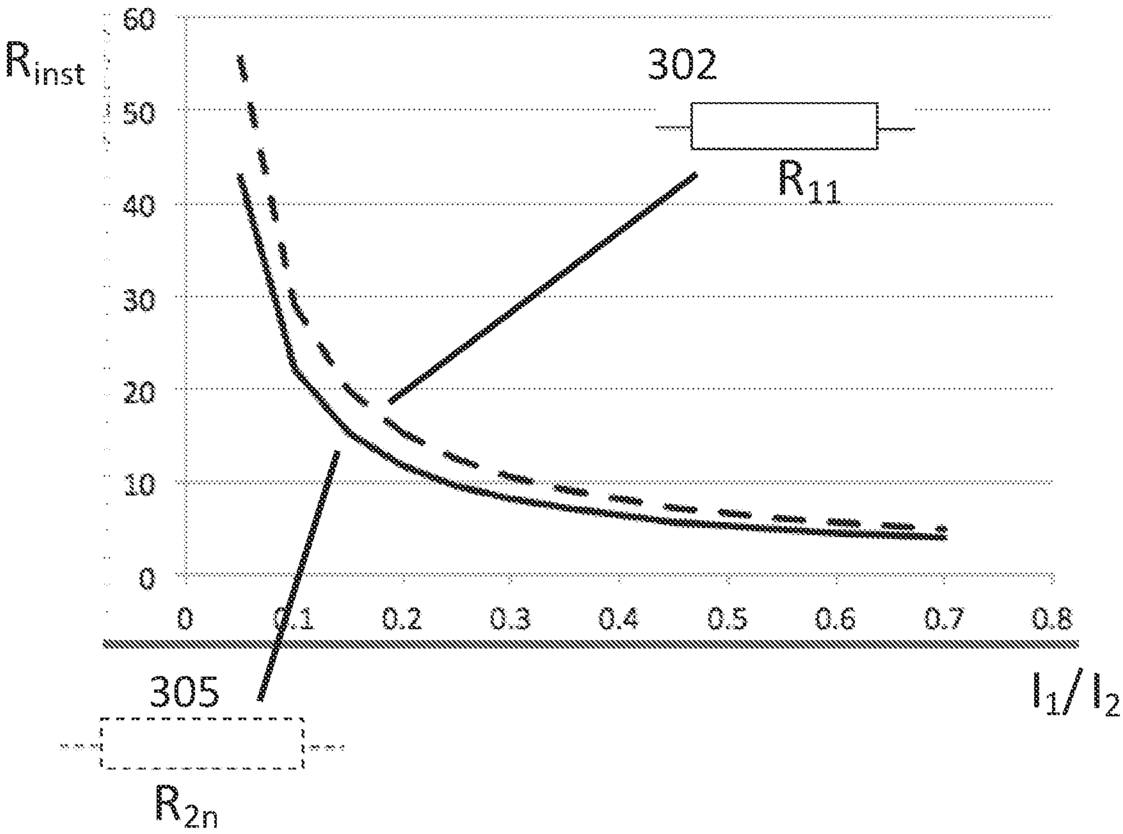
241

Fig. 2E



R_{inst}
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50
40
30
20
10
0
302
R_{11}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
305
I_1/I_2
R_{2n}

Fig. 3A

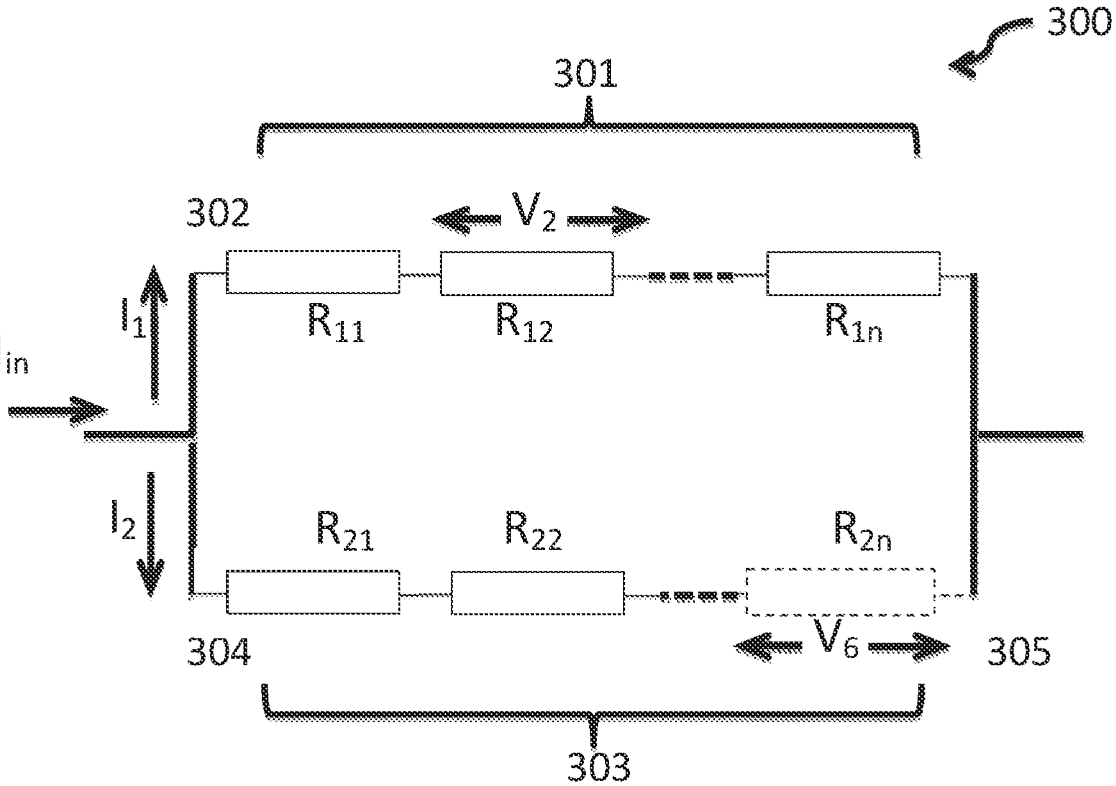


Fig. 3B

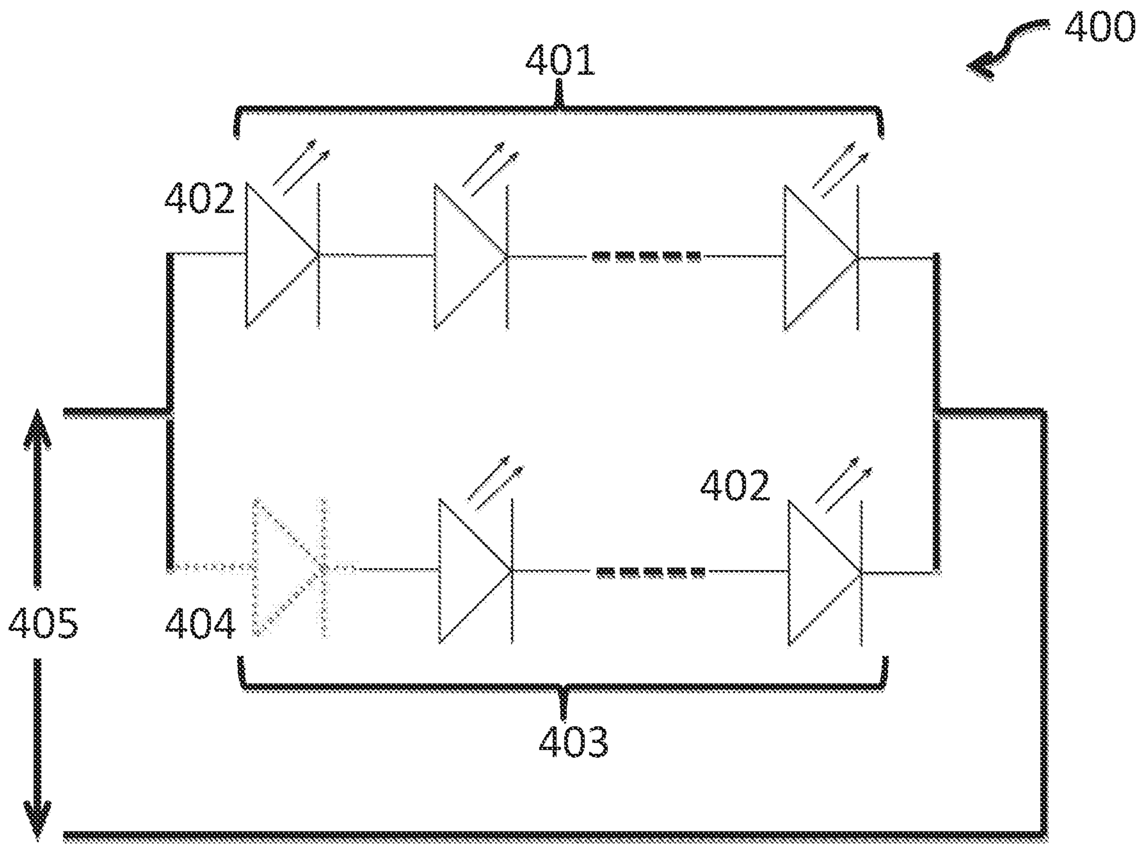


Fig. 4

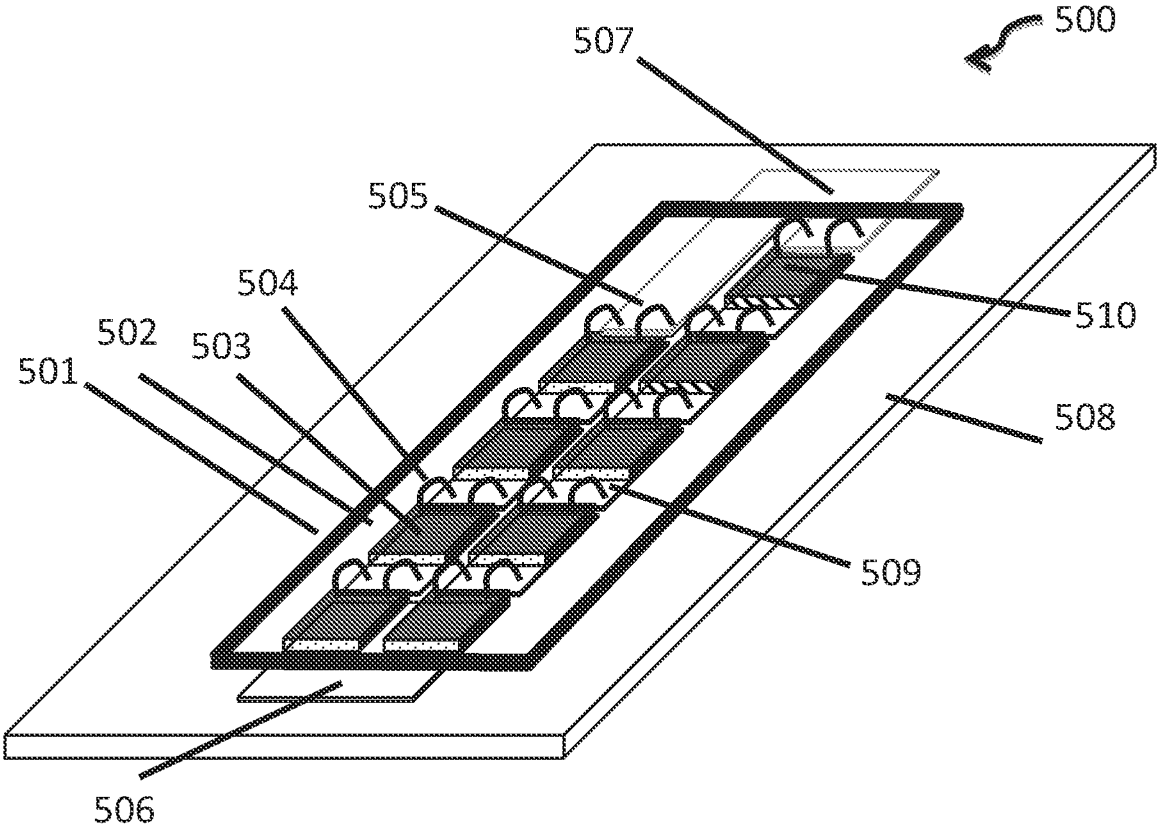


Fig. 5

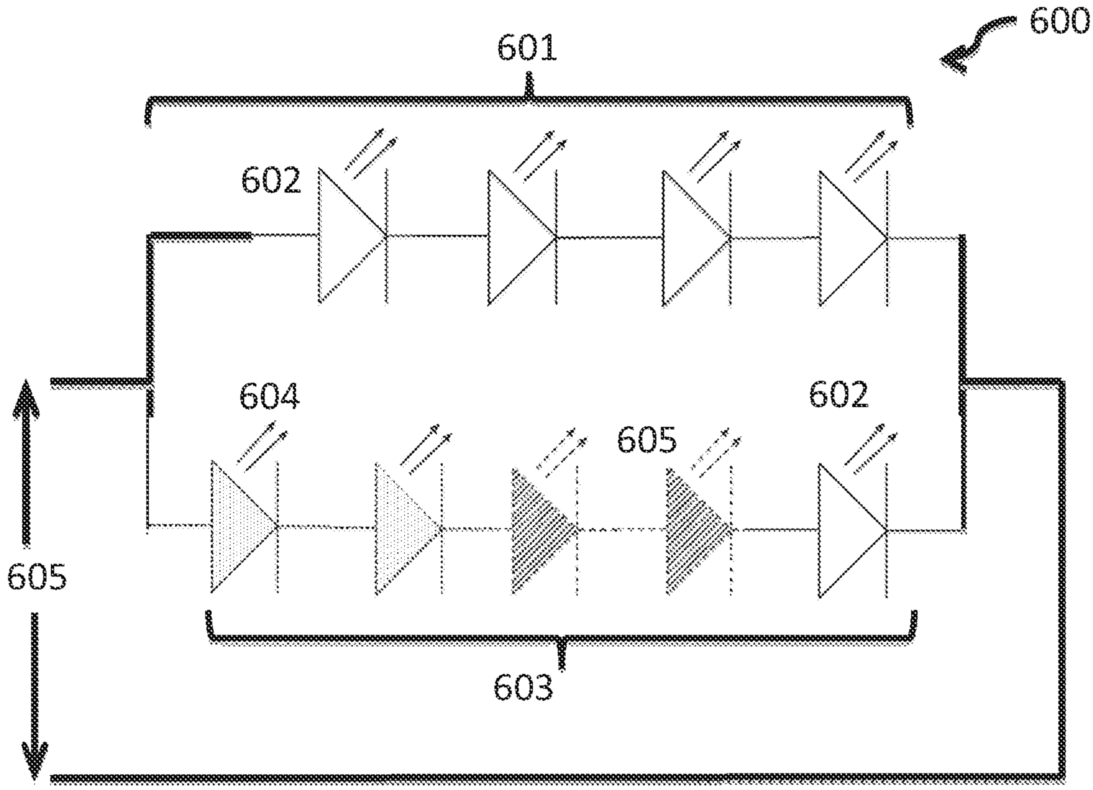
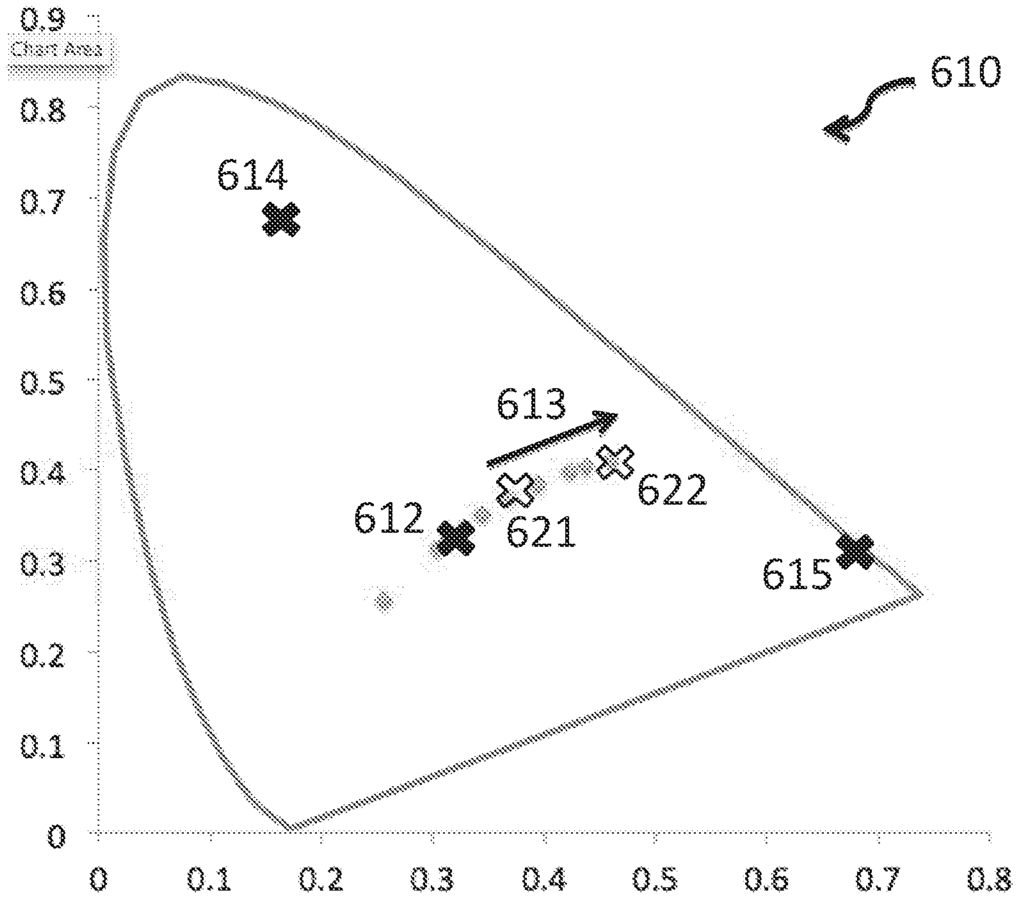


Fig. 6A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0.8
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612
621
615

Fig. 6B

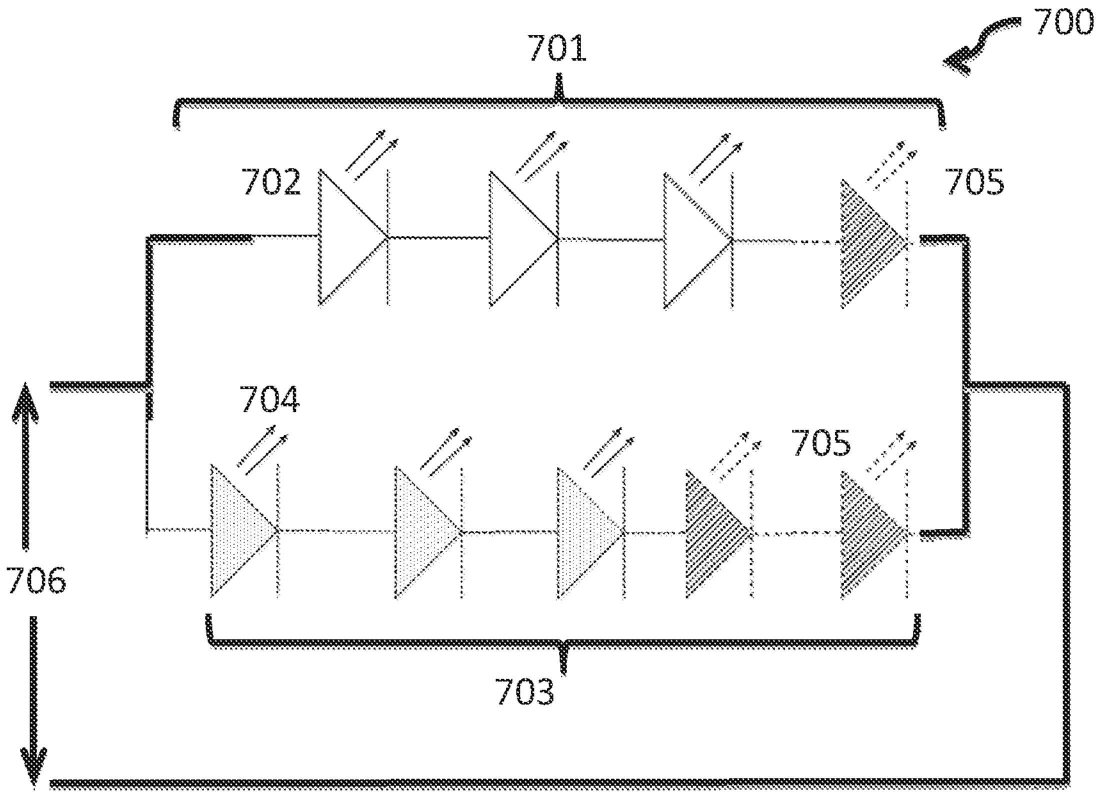
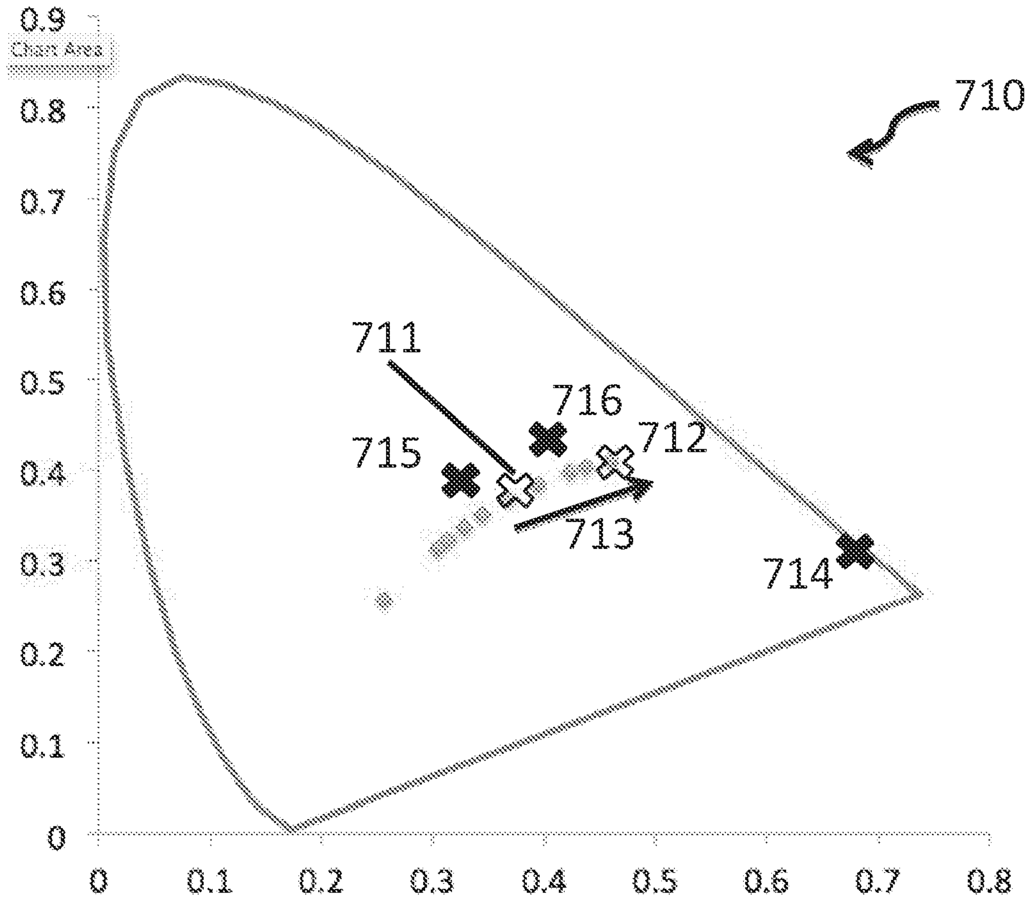


Fig. 7A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0.3
0.4
0.5
0.6
0.7
0.8
710
711
716
715
712
713
714

Fig. 7B