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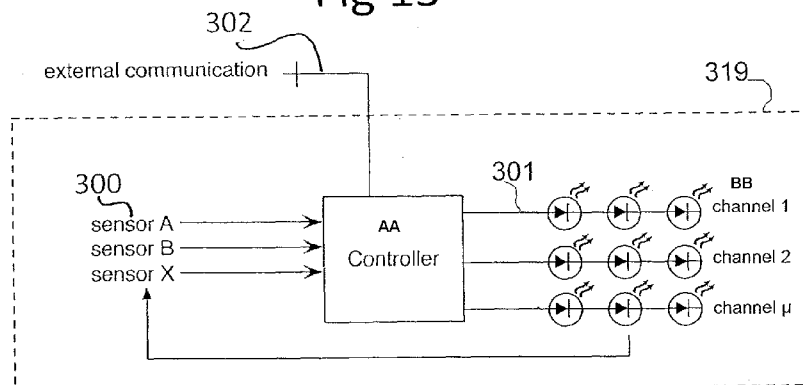
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(54) Title: LED LIGHTING SYSTEM

**Fig 15**



(57) Abstract: A system and method involving lighting fixtures, a control network, a controller and other devices such as light sensors, input devices and network adapters for coordinating precise brightness and color schedules among the lighting fixtures while maintaining a high color reliability including provisions for managing a plurality of lighting fixtures. The lighting fixtures contain lighting elements selected such that when controlled properly, operating along a daytime locus, the resultant light output closely resembles sunlight on a cloudless day in spectral characteristics, and wherein the total flux of blue light can be adjusted from a relative level of 1-100% the maximum blue flux of the lighting fixture by controlling individual lighting elements.

## LED LIGHTING SYSTEM

### SPECIFICATION

#### CROSS-REFERENCE TO RELATED APPLICATIONS

5 This utility application claims the benefit under 35 U.S.C. §119(e) of Provisional Application Serial No. 61/249,858 filed on October 8, 2009 entitled LED LIGHTING SYSTEM and whose entire disclosure is incorporated by reference herein.

#### BACKGROUND OF THE INVENTION

##### 1. FIELD OF INVENTION

10 The present invention generally relates to the field of lighting devices, and more particularly, to a system and method of controlling lighting fixtures for coordinating precise brightness and color schedules so as to closely resemble sunlight on a cloudless day in spectral characteristics.

##### 2. DESCRIPTION OF RELATED ART

15 With growing demand for energy efficient lighting, new lighting technologies such as LEDs offer distinct opportunities due to their customizable colors and precision in control. As the white LED lighting market grows, advancing the state of the art entails a seamless integration of artificial light with natural light and healthful lighting through dynamic lighting.

20 One particular niche of such LED design and control is in the generation of artificial sunlight for variety of reasons, especially for treating human ailments, e.g., circadian rhythm disorders, seasonal affection disorders, shift work conditions, etc.

25 U.S. Patent No. 6,350,275 (Vreman et al.) relates to a pair of personal glasses with built in LED's within 3 cm of the eye which directs red and blue light into the user's eyes to treat circadian rhythm disorders. However, this invention is limited to one user, must be worn during the working period and does not simulate natural sunlight.

30 The following patents propose similar methods of treating circadian rhythm disorders, but wherein they do not replicate natural sunlight conditions, involve a portable or wearable device, involve treatment periods which are intermittent and require that the patient engage with the device, or involve chromatic properties of treatment light which are not defined: U.S. Patent Nos. 5,503,637 (Kyricos, et al.); 6,053,936 (Koyama, et al.); 5,197,941 (Whitaker); 5,545,192 (Czeisler, et al.); 5,176,133 (Czeisler, et al.); and 5,304,212 (Czeisler, et al.).

Examples of other lighting control systems are mentioned below:

U.S. Patent No. 7,014,336 (Ducharme, et al.) relates to active circuitry with a feedback mechanism for reading the light in the room and actively adjusts. In particular, the invention relates specifically to color temperature variable lighting fixtures but without relating a specific region of the blackbody curve or chromaticity diagram. It also does not appear to teach or suggest a method for automatically adjusting the color temperature and brightness of the lighting fixtures without user input.

U.S. Patent No. 7,213,940 (Van De Ven et al.) involves reducing light with specific coordinates (dimming and feedback) utilizing different families of LED emitters and adjusts for specific output at constant color temperature at a sacrifice of brightness. This patent is also static embedded systems with controls within the fixture. This invention relates to a variable color temperature adjustable over time with active controls. In particular, the invention involves a specific 5-sided bounding box on the CIE (Commission Internationale de l'Eclairage) 1931 chromaticity diagram. It specifies that a first group of lighting elements must have chromaticity coordinates at a first point (defined) and a second group must have coordinates falling within the defined box. Additionally, this patent relates to a lighting fixture producing a fixed color temperature.

U.S. Patent No. 7,354,172 (Chemel, et al.) relates to rendering lighting conditions based on a reference color gamut common to many lighting units in a network using white and monochromatic LEDs. This patent does not specifically define the color gamut or the colors or chromaticity coordinates the fixture operates at, and does not appear to teach or suggest a means by which brightness and color are autonomously and dynamically changed with time.

U.S. Patent No. 6,459,919 (Lys, et al.) discloses illumination of living tissues where known light parameters relate to a condition of the living tissue. This is discussed in the context of using light to identify abnormal features and pathological conditions of tissues, living matter, and other materials. The therapeutic applications mentioned in the background extend only to diagnostic methods, and do not appear to teach or suggest using lighting conditions to stimulate a biological response.

U.S. Patent No. 6,441,558 (Muthu, et al.) relates to a fixture employing red, green, and blue LEDs and a control mechanism such that the fixture outputs a constant color temperature and brightness.

U.S. Patent No. 6,340,868 (Lys, et al.) relates to lighting units on a network capable of receiving addressing commands and controls for controlling a plurality of LEDs in each unit. However, this invention does not deal with methods by which lighting conditions are changed (i.e. color schedules), specific chromatic regions the fixtures recreate, or methods to ensure color consistency (i.e. feedback loops or sensors).

U.S. Patent No. 7,173,384 (Plotz, et al.) relates to recreating a predetermined region on a CIE chromaticity diagram using pulse width channels of red, green, and blue LEDs arranged in channels of up to six.

U.S. Patent No. 7,067,995 (Gunter, et al.) discloses the use of a temperature sensor and calibrations, along with sensor calibration data storage at various reference temperatures as a means of correcting color fluctuations related to the thermal state of the LEDs.

U.S. Patent No. 6,992,803 (Chang) relates to a feedback mechanism which calculates the chromaticity coordinates of each lighting element in a lighting fixture to calculate the proper operating conditions necessary to reproduce a specific chromaticity coordinate.

U.S. Patent No. 6,683,419 (Kriparos) discloses a method by which LEDs, with linear dimming - brightness curves, mimic incandescent bulbs, which have exponential dimming - brightness curves. The invention involves the dimming-brightness relationship in an LED fixture and does not appear to teach or suggest changing color with dimming level.

U.S. Patent No. 7,327,337 (Callahan) involves a series of lighting devices connected to a two wire power bus in which the color modulation signals are transmitted through the power connection and demodulated in the lighting device.

U.S. Patent No. 6,806,659 (Mueller, et al.) covers a lighting control network for LED luminaires as well as various LED lighting fixtures for several applications. See also U.S. Patent Publication No. 20040178751 (Mueller, et al.).

U.S. Patent No. 4,962,687 (Belliveau, et al.) deals with variable colors in a lighting system achieved by dimming circuitry within fixtures. It does not appear to cover specific chromatic regions rendered using a control feedback loop.

U.S. Patent No. 5,350,977 (Hamamoto, et al.) involves a variable color temperature fixture, and does not incorporate a means of autonomously and dynamically

changing the color temperature and or brightness with respect to the time of day or geographic location.

U.S. Patent No. 5,357,170 (Luchaco, et al.) claims a control system where preset conditions can be changed by the occupant by moving a physical member or slider control to change the maximum brightness levels of the system. This patent does not  
5 appear to address color modulation over time or lighting schedules or programs.

U.S. Patent No. 7,288,902 (Melanson) deals first with a lighting fixture with two unique lighting elements, each possessing a fixed color temperature, which are then dimmed at different ratios relative to the AC power dimming level to achieve a variable  
10 color temperature with dimming level. This patent claims only "white" and "yellow" LEDs, and does not appear to teach or suggest the ratios or specific chromatic region rendered by the lighting device. This patent also does not appear to teach or suggest any method by which a control system can interface with a fixture, or any method by which the brightness and color temperature of the fixture can be controlled independently.

U.S. Patent No. 6,720,745 (Lys, et al.) discloses the use of the RS-485 standard  
15 to control a plurality of LED devices.

U.S. Patent No. 7,215,086 (Maxik), issued relates to integrating the fixture designs within the Lutron Circuits to achieve dimming levels below 5% through pulse modulation. This invention utilizes a square wave which has been discussed in prior  
20 art.

U.S. Patent No. 5,193,900 (Yano, et al.) discloses a device which detects natural light and mechanically actuates a filter on an artificial light source.

U.S. Patent No. 6,554,439 (Telcher, et al.) teaches a method of treating circadian rhythm disorders using light sources and a rotating filter.

U.S. Patent No. 7,446,303 (Maniam, et al.) discloses an ambient light sensor suitable for determining lighting conditions, but does not practice a lighting device  
25 or a system of lighting devices.

U.S. Patent Nos. 7,387,405 and 7,520,634 (Ducharme, et al.) pertain to a system of lighting devices capable of producing a broad range of lighting conditions,  
30 however they do not utilize a specific collection of at least three lighting elements of a characteristic chromaticity (as is disclosed in the present application, as will be discussed later), and do not teach a method by which the user can prescribe a particular flux of blue light within white light.

U.S. Patent No. 7,319,298 (Jungwirth, et al.) relates to a luminaire system which produces light of a desired chromaticity and luminous flux output with varying ambient temperature. The prior art teaches a method by which the luminaire regulates chromaticity throughout changing temperatures using sensors.

5 U.S. Patent No. 5,721,471 (Begemann, et al.) discloses a lighting system which manipulates artificial lighting based on actual lighting conditions, determined either by a light sensor exposed to natural light or by the calendar day and time of day. It also discusses modification to artificial lighting conditions based on a modification to present mean day-lighting levels. In contrast (as will be discussed in  
10 detail later), the present invention relates a desired result or circadian response to the generation of signals to control lighting devices and the ultimate generation of artificial light. This method of input is based on user preference rather than a prescriptive input based on a default time of day or existing lighting conditions for a fixed geographic location. The present invention allows the user to adjust for jet lag  
15 after travel, maintain the lighting conditions of a fixed geographic location throughout any location, coordinate the circadian rhythm to a cycle other than 24 hours, or specify a desired circadian response or condition.

U.S. Patent No. 7,679,281 (Do Hyung, et al.) teaches a lighting device with three lighting elements, two of which comprise an LED chip combined with a  
20 phosphor of a specific composition and a third LED chip which emits light in the visible range of 580nm or more. This third lighting device emitting visible light of 580nm is described as a lighting element which produces light of 3000K or less, however no specific spectral distributions of light are disclosed. In contrast (and as will be discussed in detail later), the present invention relates to a collection of  
25 lighting elements with specific chromaticity characteristics such that the flux of blue light can be precisely controlled through independent modulation of each lighting element while maintaining high color rendering index of the artificial white light. The selection of the lighting elements in the present invention may comprise any collection of lighting elements which produce light in the characteristic chromaticity  
30 regions described in Figs.13a -14b of the present application. Furthermore, it is within the scope of the present invention that any lighting device of a characteristic chromaticity illustrated in Figs.13a-14b of the present application be used to generate artificial light of high color rendering index in the range of 1800-6500K.

These lighting devices may be composed of (but are not limited to) LED chips, LEDs combined with phosphors, LED chips combined with quantum dots, LED chips combined with photonic crystals, organic light emitting diodes (OLED), or polymeric LED devices (PLED).

5 U.S. Patent Publication No. 20030133292 (Mueller, et al.) discloses many applications of color temperature variable lighting. Daylight simulation and circadian rhythm disorder treatment is not mentioned.

U.S. Patent Publication No. 20030100837 (Lys, et al.) relates to therapeutic effects achieved with LED devices; it claims: an LED system for generating a range of colors within a color spectrum, selecting from the range of colors a set of colors, whereby the set of colors produces in the patient a therapeutic effect, and illuminating an area of the patient with the set of colors for a period of time predetermined to be effective in producing the therapeutic effect. The patent does not appear to identify the range of colors which produce the therapeutic effect, nor does it appear to identify a period of time or method of modulation of the light to facilitate this therapeutic effect.

15 See also the following U.S. patent publications regarding LED lighting controls: U.S. Patent Publication Nos. 20050253533 (Lys, et al.); 20050236998 (Mueller, et al.); 20050231133 (Lys); 20050218870 (Lys); 20050213353 (Lys); 20050200578 (Lee, et al.); 20050151489 (Lys); 20040212321 (Lys, et al.); and 20040105264 (Spero).

20 However, despite the foregoing, there remains a need for a system and method that generates broad spectrum white light of color temperatures 1800K to 6500K in interior spaces using general lighting fixtures (e.g., for treating circadian rhythm disorders) and wherein brightness and color are autonomously and dynamically changed with time and while using combinations of white LEDs and color LEDs. Furthermore, there remains a need for such a system and method that does not require calculating chromaticity coordinates but rather uses calibration values of sensor outputs at specific color temperatures and preferably, for controlling a feedback loop, and a color matching algorithm.

#### BRIEF SUMMARY OF THE INVENTION

30 The invention also comprises a novel method to control lighting devices (e.g., novel methods of interpreting given user input into control signals which translate to a specific point on the daylight locus or color temperature) as well as a novel lighting device. This is significant because variable color temperature fixtures

(e.g., those shown in the prior art) are designed to be controlled, operated, or programmed by lighting designers or advanced users. As will be discussed in detail below, the present invention incorporates methods by which simple inputs are translated into appropriate signals for controlling a multi-channel lighting device.

5 These simple inputs may comprise

- 1) dimming level;
- 2) dimming level and color temperature level;
- 3) time of day;
- 4) time zone;
- 10 5) geographic location;
- 6) desired circadian response;
- 7) present activity (e.g., sleep, reading, working, studying, eating, resting, etc); and
- 8) angle of sun.

These inputs can be manually inputted to the system or they can be  
15 automatically fed to the system from sensors (e.g., clocks, global positioning systems, etc.).

A further input to this novel system is the flux of color light, and more preferably, the flux of blue light flux of blue light (specifically 464nm). Furthermore, “blue light”, referred to as specifically 464nm light, is meant to be interpreted to be  
20 broad spectrum blue light with a concentration (spectral peak) at approximately 464nm.

Also note that a lighting system with a shorter range of 3500-5000K for example can still satisfy the requirements to coordinate circadian rhythms by regulating output of blue light (specifically the flux of 464nm light). It is within the  
25 scope of the invention that a lighting device comprising at least three lighting elements of characteristic chromaticity illustrated in Figs. 13a-14b may be limited to the range of 3000-6000K for example based on the balance of lighting elements in the fixture. Furthermore, a lighting device comprising at least three lighting elements of the characteristic chromaticity illustrated in Figs. 13a-14b where each lighting  
30 device outputs at any flux level is within the scope of the present invention.

In one example, the circadian rhythm of a subject is regulated or affected by artificial light where the flux of blue light (specifically 464 nm) is adjusted through changes in color temperature, brightness, or both. This example teaches that even



warm white light contains a quantity of blue light which can influence a circadian response, and that light of a constant color temperature can be modulated in intensity to induce a circadian response.

5 It should be noted that because the prior art does not take into account the flux of light in the blue region (specifically 464nm) in white light control mechanisms, methods, and systems, it is possible that prescriptive efforts to regulate a subject's circadian rhythm can have undesirable results since all white light contains blue light. Because of this, simple modulation of color temperature alone is not adequate to affect a desired circadian response.

10 Note the fact that users may want to adjust lighting to emulate very warm, dimmed incandescent lighting with a characteristic color temperature of 1800-2400K. This characteristic color temperature also contains a very small fraction of irradiance in the blue region (in particular the 464nm wavelength) compared to light in the 5000-6500K region. A lighting system of fixtures capable of producing light  
15 in the 1800-2400K region offers the user more options to coordinate lighting in such a way that the circadian rhythm is not disrupted by blue light.

A system is disclosed for artificially generating sunlight in accordance with a daytime locus using spectral characteristics that resembles sunlight (including other variations of daytime sunlight such as diffuse lighting, e.g., cloudless, partially  
20 cloudy, overcast, foggy, rainy, snowy, etc.). The system automatically controls at least one lighting fixture substantially along a daytime locus (e.g., white light of color temperature from 1800K to 6500K) to generate the artificial sunlight.

A method is disclosed for artificially generating sunlight in accordance with a daytime locus using spectral characteristics that resembles sunlight (including other variations of daytime sunlight such as diffuse lighting, e.g., cloudless, partially cloudy,  
25 overcast, foggy, rainy, etc.). The method comprises: providing a plurality of channels of lighting elements (e.g., at least three channels); activating the plurality of channels to generate a composite light mixture; detecting the composite light mixture; and controlling the plurality of channels of lighting elements based on the detected  
30 composite light mixture to generate artificial sunlight mixture (e.g., white light of color temperature from 1800K to 6500K) along the daytime locus.

An artificial sunlight system is disclosed wherein the system comprises a lighting fixture whose light output is automatically controlled to reduce the effects of, or

treat, one of the group of circadian rhythm disorders, shift work dysfunction and seasonal affective disorder by operating along a daytime locus (e.g., white light of color temperature from 1800K to 6500K) to provide compensating artificial sunlight.

5 A method is disclosed for artificially generating sunlight in accordance with a daytime locus (e.g., white light of color temperature from 1800K to 6500K) using spectral characteristics that resembles sunlight (including other variations of daytime sunlight such as diffuse lighting, e.g., cloudless, partially cloudy, overcast, foggy, rainy, etc.). The method comprises: providing a plurality of channels of lighting elements; activating the plurality of channels to generate a composite light mixture; detecting the  
10 composite light mixture; and controlling the plurality of channels of lighting elements based on the detected composite light mixture to generate artificial sunlight along the daytime locus for reducing the effects of, or treating, one of the group of circadian rhythm disorders, shift work dysfunction and seasonal affective disorder by operating along the daytime locus to provide compensating artificial sunlight.

15 A system for artificially generating sunlight in accordance with a daytime locus (e.g., white light of color temperature from 1800K to 6500K) using spectral characteristics that resembles sunlight (including other variations of daytime sunlight such as diffuse lighting, e.g., cloudless, partially cloudy, overcast, foggy, rainy, snowy, etc.). The system automatically controls at least one lighting fixture substantially along  
20 the daytime locus to generate the artificial sunlight wherein the system automatically changes brightness levels and color levels of a plurality of lighting element channels within the at least one lighting fixture that generates broad spectrum white light of color temperatures from 1800K to 6500K in accordance with a user-selected input. Furthermore, the system controls a total flux of blue light (e.g., 464nm) from a relative  
25 level of 1 to 100% of a maximum blue light flux within the broad spectrum white light.

A method is disclosed for artificially generating sunlight in accordance with a daytime locus (e.g., white light of color temperature from 1800K to 6500K) using spectral characteristics that resembles sunlight (including other variations of daytime sunlight such as diffuse lighting, e.g., cloudless, partially cloudy, overcast, foggy, rainy,  
30 snowy, etc.). The method comprises: providing a plurality of channels of lighting elements (e.g., at least three channels); activating the plurality of channels to generate a composite light mixture; detecting the composite light mixture; controlling a total flux of blue light (e.g., 464nm) which can be adjusted from a relative level of 1 to 100% of a

maximum blue light flux of said composite light mixture; and controlling said plurality of channels of lighting elements based on said detected composite light mixture to generate artificial sunlight along the daytime locus having a broad spectrum white light of color temperatures from 1800K to 6500K.

5           It should be understood that although the preferred color temperature range of operation of the present system and method is 1800K to 6500K, this is by way of example only and may vary. The important feature of the present invention is the artificial generation of a whole range of sunlight scenarios (such as diffuse lighting, e.g., cloudless, partially cloudy, overcast, foggy, rainy, snowy, etc.) which includes any type  
10           of sunlight that occurs during the daytime using direct lighting. Thus, it is within the broadest scope of the present invention to include the artificial generation of all kinds of sunlight, including diffuse lighting (e.g., diffuse UV radiation) via the system/method of the present invention.

          In addition, the phrase "daylight locus" as used throughout this Specification is  
15           close in proximity to the Planckian Blackbody Curve.

#### BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

The invention will be described in conjunction with the following drawings in which like reference numerals designate like elements and wherein:

20           Fig. 1 shows a blackbody curve on a 1931 CIE XY chromaticity diagram, depicting the chromatic regions over which the present invention operates;

          Fig. 1b depicts the chromaticity change of the sunlight as the sun progresses through the day;

          Fig. 2 illustrates four points on an XY chromaticity diagram corresponding to Kelvin scale-correlated color temperatures of 6500K, 5400K, 4200K and 3200K;

25           Fig. 3 is an enlargement of the XY chromaticity diagram of Fig. 2 corresponding to the Kelvin scale-correlated color temperatures of 6500K, 5400K, 4200K and 3200K;

          Fig. 4 depicts an initial condition of chromaticity x, y coordinates for exemplary lighting elements;

30           Fig. 5 depicts the chromaticity x,y coordinates for the exemplary lighting elements of Fig. 4 but at after 50,000 hours;

          Fig. 6 depicts the relationship between the excitation and emission spectrum of the exemplary lighting elements, showing the spectrum at initial conditions and at 50,000 hours;

Fig. 7 depicts the angular relationship between the sun and the earth, as well as the corresponding change of path length traveled by lightwaves through the atmosphere layer;

Fig. 8 is an equation relating air mass to the zenith angle,  $\phi_z$ ;

5 Fig. 9 depicts the changes in the spectral distribution of sunlight with air mass;

Fig. 10 is an exploded view of an exemplary lighting element of the present invention;

Fig. 11 is a side view of the lighting element of Fig. 10;

10 Fig. 12 is an exploded view of an alternative lighting element of the present invention;

Fig. 13a depicts three exemplary boundary boxes of lighting elements that can be used in the present invention to generate a color space;

Fig. 13b depicts an exemplary color space that can be generated using the three exemplary boundary boxes of lighting elements of Fig. 13a;

15 Fig. 14a depicts four exemplary boundary boxes of lighting elements that can be used in the present invention to generate another color space;

Fig. 14b depicts an exemplary color space that can be generated using the four exemplary boundary boxes of lighting elements of Fig. 14a;

20 Fig. 15 comprises a block diagram of a portion of the system of the present invention wherein a controller receives optical sensor outputs for controlling lighting element operation;

Fig. 16 comprises a block diagram of the system of Fig. 15 but including amplifier stages prior to the lighting elements;

25 Fig. 17 depicts the consolidation of the lighting elements into one or more devices, such as multi-channel amplifiers or multi-channel drivers;

Fig. 18 depicts multiplexed devices, such as lighting elements, sensors, amplifiers, as well as other devices combined on a common digital bus;

Fig. 19 shows the use of multiple arrays or collections of devices within common spatial regions which are combined on a common digital bus;

30 Fig. 20 is flow diagram of the sensor activation sequence;

Fig. 21 is an amplitude vs. time plot for three groups (by way of example only) of lighting elements in close spatial proximity wherein each group is activated sequentially in time during calibration;

Fig. 22 depicts the sensor output voltages that monitor each lighting element in each group when they are activated for calibration;

Fig. 23 is a chart of the recorded sensor voltages for each element in each group during calibration;

5 Fig. 24 is a block diagram of a light fixture control system of the present invention using a non-serial network (e.g., Ethernet);

Fig. 25 is a block diagram of a light fixture control system as shown in Fig. 25 but including light sensor and user controls;

10 Fig. 26 is a block diagram of a light fixture control system as shown in Fig. 26 but including an extended reach via the use of network adapters;

Fig. 27 is a plot of correlated color temperature vs. time of day used in the present invention for controlling one or more light fixtures;

Fig. 28 is a plot showing how light fixture brightness may be altered by the present invention during a 24 hour period;

15 Fig. 29 is an alternative plot showing, brightness, color temperature, and time being assigned graphically using an interface consisting of sliders and zones;

Fig. 30 depicts a user interface for controlling the system of the present invention;

Fig. 31 shows a further variation of the system of the present invention which permits remote control of the system via a cellular phone, PDA, notebook computer,  
20 etc.;

Fig. 32 shows exemplary user interface applications for use on the remote devices for controlling the system of the present invention;

Fig. 33 is a block diagram depicting how a desktop computer can be used to interface with a lighting control network of the present invention;

25 Fig. 34 depicts three exemplary user control panels within a graphical user interface;

Fig. 35 depicts a transimpedance amplifier circuit which is used to convert current values from the light sensors into voltages;

30 Fig. 36 depicts a transimpedance amplifier circuit which can convert multiple sensor input currents into voltages;

Fig. 37 is a chart relating the effective range the transimpedance amplifier is effective for a given resistor setting; and

Fig. 38 is a chart depicting how the system/method of the present invention may be used to acclimate a subject to a 36-hour day, rather than a 24-hour day.

#### DETAILED DESCRIPTION OF THE INVENTION

Although there are many uses of the invention of the present application, one of the most important is circadian rhythm applications. Circadian rhythm disturbances may be circadian rhythm imbalances, hormonal imbalances activated by exposure to light, shift work condition, or seasonal affective disorder. In particular, the invention of the present application comprises a lighting system which can treat and prevent circadian rhythm disorders. Also included within the broadest aspect of this invention are other applications where prevention of shift work dysfunction, seasonal affective disorder, and circadian rhythm disorders is mission critical, such as military applications (including navy vessels) and manned aerospace applications. Furthermore, the utility of the present invention can be invoked in geographic locations where the sky is often overcast or sunlight is scarce. The invention would equally apply to travelers since jet lag is related to the circadian rhythm. This application has customers in the passenger rail industry, airline industry, and hospitality industry.

Furthermore, the benefits of low glare, high CRI (Color Rendering Index) daylight white lighting extend beyond health benefits. Studies have shown increases in productivity, retail sales, and classroom performance in daylight-lit spaces. For these reasons, the present invention can provide greater efficiencies in retail applications, office and commercial applications, and education/higher education applications. In fact, retailers may find it useful to display their products in the optimal type of light, to further enhance every bit of the shopping experience. Restaurants which serve patrons from morning through the evening often use several circuits of incandescent lights or dimmers to change the lighting conditions throughout the day. A lighting system, such as the present invention, that keeps patrons comfortable at breakfast while being able to deliver a warm intimate atmosphere at cocktail hour is particularly appealing in this regard.

In Fig 1, the blackbody curve 200 (also referred to as the “daylight locus”) is plotted on a 1931 CIE (Commission Internationale de l’Eclairage) XY chromaticity diagram 201, illustrating the chromatic regions through which the invention operates. In Fig. 2, four points 210, 211, 212, and 213 are represented on a similar XY chromaticity diagram 209 on the blackbody curve 208 corresponding to the Kelvin scale correlated

color temperatures (CCT) of 6500K, 5400K, 4200K, and 3200K – an alternate method of specifying regions on the chromaticity diagram.

Fig. 1b depicts the relative positions on the XY chromaticity diagram where direct sunlight may be characterized by measure of air masses traversed at ground level.

5 Reference point 204 indicates the point where direct sunlight with clear skies at an air mass of 1.0 would be positioned on the CIE chromaticity diagram, which is accepted to be approximately 6500K by measure of correlated color temperature by those skilled in the art. Reference point 205 corresponds to an air mass of  $>1$ , while reference points 207 and 208 correspond to higher air masses  $\geq 5$  and  $\geq 10$ , respectively. This bounding  
10 box encloses the blackbody curve along which the sun's chromaticity coordinates vary from 1-37 air masses. Special considerations are given for spectral shifts during the lifetime of the lighting fixture, ensuring that after the lighting elements decay, the bounding box will sufficiently cover the chromaticity points corresponding to the sun's spectral distribution between air masses 1 and 37.

15 For the purposes of describing white light, it is useful to truncate the CIE 1931 chromaticity diagram to the region of interest. The diagram in Fig. 3 shows correlated color temperature in degrees Kelvin at points 214 (6500K), 215 (5400K), 216 (4200K), and 217 (3200K) in a similar fashion as Fig. 2.

Bounding boxes 230, commonly referred to as "bins" by those versed in the art,  
20 are represented on an x-y chromaticity diagram 231. A bounding box, or bin, can be described by four coordinate points on the chromaticity diagram. A bin describes a sampling of lighting elements possessing a distribution of chromaticity characteristics defined within the bounding box, and various nomenclature systems may be used to describe individual bounding boxes or bins, a term used by those practiced in the art. A  
25 sampling of many lighting element's chromaticity characteristics can be plotted on a chromaticity coordinate system and arranged into bins, where the chromaticity characteristics are determined by optical testing. The dimensions of the bin (area on the x-y chromaticity chart) describes the variation in the spectral distribution for a given sample of similar lighting elements.

30 Any lighting element is subject to various modes of optical decay, dissipation, or degradation. These modes of decay may be related to brightness decreases (lumen decay) or spectral shifts throughout the lifetime of the lighting element. Spectral shifts may also occur due to the thermal state or variations in the operating voltage of a

lighting element. Many solid state lighting elements produce broad spectrum light by down converting high frequency monochromatic light (herein referred to as excitation source) into broad spectrum lower frequency emission using specialized downconverters or lumiphors. These downconverters may consist of phosphors, quantum dots, organic semiconducting materials, photonic crystals, nano photonic crystals, and other photonic crystals. These various downconverters are subject to modes of degradation or decay, such as quantum efficiency decay, spectral shifting, thermal decay, oxidation, excitation peak shifts, and emission shift to name a few.

Four lighting element at points 231, 232, 233, and 234 possessing unique specific chromaticity coordinates are represented at an initial condition in Fig. 4. In such initial condition, the thermal state attribute, forward voltage attribute, lifetime attribute, degradation state, or a combination of any of these attributes is within predetermined limits. It should be noted that the thermal state attribute describes the junction temperature, influenced by ambient temperature, lighting fixture temperature, or increased temperature due to operation. The lifetime attribute describes the total active operating time, and the degradation state describes the condition of the lighting element due to events such as oxidation, over heating, or operating time brightness decay.

In a second condition, one or a combination of several operating attributes has changed from the initial condition. Changing one or a combination of these attributes causes a change in the lighting element's optical chromaticity coordinate, shown in Fig. 5 for points 235, 236, 237, and 238. For example, in the initial condition described by Fig. 4, the lighting elements have not been operated and are at a lifetime of 0 hours. In the second condition described by Fig. 5, the lighting elements have been operated for 50,000 hours and possess different chromaticity x, y coordinates.

In the case of degradation due to operating time, the relationship between the excitation and emission spectrum is described by Fig. 6. The spectral characteristics of a lighting element at zero operation hours, or an initial condition, is represented as a solid line 219 on a wavelength scale 218. The spectral characteristics of a lighting element at 50,000 operating hours is represented as a dashed, discontinuous line 221 on the same wavelength scale 218.

In an initial condition where lighting elements are at an operating lifetime of 0 hours, the excitation intensity is at a higher level 220 than the excitation intensity in a degraded state, 222. Similarly, the broad band converted light goes from an initial high



intensity 219 to a lower intensity in a degraded state 221.

Fig. 7 describes the angular relationship between the sun 240 and the earth 241, along with the corresponding change of path length 244 traveled through the atmosphere layer 242. As the sun's angle, here in referred to as zenith angle,  $\phi_z$ , 243 changes with respect to a fixed point on the earth's surface 241, the path length 244, herein referred to as air mass, of the light through the atmosphere layer changes. The boundaries of the zenith angle 243 correspond to the horizons observed from the ground, and are  $-90^\circ$  and  $+90^\circ$ . This path length is commonly measured in the unit of air masses. For example, a zenith angle 243 of  $0^\circ$  between the sun and earth's surface corresponds to an air mass of 1.0, while a zenith angle 243 of  $90^\circ$  corresponds to an air mass of 38.

Fig. 8 is an expression which relates air mass 245 to any given zenith angle 246 of the sun. This zenith angle 246 can further be related to the geographic location on the earth's surface, the time of day, and the date.

Fig. 9 describes the changes in the spectral distribution of sunlight with air mass. It is shown that for a high air mass 246 of 10, a significant decrease in wavelengths 450-600 is present relative to an air mass 247 of 1, as well as a decrease in total irradiance relative to an air mass 247 of 1.

Fig. 10 provides an exemplary lighting fixture 319 of the present invention. The lighting fixture 319 comprises solid state lighting elements 250, thermal dissipation components 251, logic and power conversion components 252, reflector 253 and optical components 257, spectrally unique sensors 258, heat sink or heat pipe 254, internal interconnects 255, and other structural housing features 256. Where, components are assembled together into unified device consisting of a fixture body 270, power interconnect 271, and optical aperture emitting illumination 272 illustrated in Fig. 11. In this embodiment, the components are assembled into a round compact fixture suitable for providing targeted light, recessing into a ceiling, or replacing a common recessed flood light. By way of example only, the sensors 258 may be formed on a single wafer or cell as shown in Fig. 10.

Similarly, these key components may be arranged in an alternate fashion. Another such lighting fixture embodiment 319A is represented in Fig. 12, where lighting elements 260, optical components 261, heat sink 262 and thermal dissipation components 263, and a housing 264 are arranged in an alternate form. In this

embodiment 319A, this alternate form is a linear fixture, suitable for lighting larger areas using a single fixture. Furthermore, in this configuration, the sensors 258a are distributed, as shown in Fig. 12.

In lighting fixtures 319/319A containing a plurality of lighting elements  
 5 250/250A, two elements possessing unique spectral characteristics can be placed in close proximity where the light emitted travels into a cavity and is reflected off of one or more surfaces, mixing the light.

Fig. 13a shows three exemplary bounding boxes 275, 276 and 277 whose lighting elements have unique spectral distributions and which, when mixed properly in the  
 10 present invention, combine to generate a color space, e.g, color space 280 shown in Fig. 13b. By way of example only, the present invention may comprise three channels of lighting elements defined as follows:

Channel 1 (cool white) comprising bounding box on x,y chromaticity diagram with four points given by (x,y). lighting elements comprising channel 1 possess  
 15 chromaticity characteristics falling within the bounding box 275:

Point one having x,y chromaticity coordinates of 0.30, 0.33;  
 Point two having x,y chromaticity coordinates of 0.35, 0.37;  
 Point three having x,y chromaticity coordinates of 0.35, 0.34; and  
 Point four having x,y chromaticity coordinates of 0.31, 0.31.

Channel 2 (warm white) comprising bounding box on x,y chromaticity diagram with four points given by (x,y). lighting elements comprising channel 2 possess  
 20 chromaticity characteristics falling within the bounding box 276:

Point one having x,y chromaticity coordinates of 0.37, 0.39;  
 25 Point two having x,y chromaticity coordinates of 0.48, 0.43;  
 Point three having x,y chromaticity coordinates of 0.46, 0.39; and  
 Point four having x,y chromaticity coordinates of 0.36, 0.35.

Channel 3 (amber) 277: comprising bounding box on x,y chromaticity diagram with four points given by (x,y). lighting elements comprising channel 3 possess  
 30 chromaticity characteristics falling within the bounding box

Point one having x,y chromaticity coordinates of 0.54, 0.42;  
 Point two having x,y chromaticity coordinates of 0.55, 0.45;  
 Point three having x,y chromaticity coordinates of 0.60, 0.40; and  
 35 Point four having x,y chromaticity coordinates of 0.57, 0.40.

Fig. 14a shows four exemplary bounding boxes 282, 283, 284 and 285 whose lighting elements have unique spectral distributions and which, when mixed properly in the present invention, combine to generate a color space, e.g, color space 286 shown in  
 40 Fig. 14b. By way of example only, the present invention may comprise four channels of

lighting elements defined as follows:

- Channel 1 (very cool white) comprising bounding box on x,y chromaticity diagram with four points given by (x,y). LED emitters comprising channel one possess chromaticity characteristics falling within the bounding box 282:
- 5 Point one having x,y chromaticity coordinates of 0.30, 0.33;  
 Point two having x,y chromaticity coordinates of 0.35, 0.37;  
 Point three having x,y chromaticity coordinates of 0.35, 0.34; and  
 Point four having x,y chromaticity coordinates of 0.31, 0.31.
- 10 Channel 2 (neutral) comprising bounding box on x,y chromaticity diagram with four points given by (x,y). lighting elements comprising channel one possess chromaticity characteristics falling within the bounding box 283:
- Point one having x,y chromaticity coordinates of 0.35, 0.37;  
 Point two having x,y chromaticity coordinates of 0.41, 0.41;  
 15 Point three having x,y chromaticity coordinates of 0.40, 0.37; and  
 Point four having x,y chromaticity coordinates of 0.35, 0.34.
- Channel 3 (warm white) comprising bounding box on x,y chromaticity diagram with four points given by (x,y). lighting elements comprising channel one possess chromaticity characteristics falling within the bounding box 284:
- 20 Point one having x,y chromaticity coordinates of 0.41, 0.41;  
 Point two having x,y chromaticity coordinates of 0.48, 0.43;  
 Point three having x,y chromaticity coordinates of 0.46, 0.39; and  
 Point four having x,y chromaticity coordinates of 0.40, 0.37.
- 25 Channel 4 (amber) comprising bounding box on x,y chromaticity diagram with four points given by (x,y). lighting elements comprising channel one possess chromaticity characteristics falling within the bounding box 285:
- Point one having x,y chromaticity coordinates of 0.54, 0.42;  
 30 Point two having x,y chromaticity coordinates of 0.55, 0.45;  
 Point three having x,y chromaticity coordinates of 0.60, 0.40; and  
 Point four having x,y chromaticity coordinates of 0.57, 0.40.

As mentioned previously, one of the unique aspects of the present invention

35 is the ability to control lighting devices, and more specifically, (as will be discussed in detail below), controlling the brightness levels and the color levels of a plurality of lighting element channels. And as also mentioned earlier, this control is effected by permitting inputs to be made (either manually or automatically):

- 1) dimming level;
- 40 2) dimming level and color temperature level;
- 3) time of day;
- 4) time zone;
- 5) geographic location;

- 6) desired circadian response;
- 7) present activity (e.g., sleep, reading, working, studying, eating, resting, etc); and
- 8) angle of sun.

A ninth input is the flux of color light, i.e., being able to control the total flux  
5 of a specific color light from a relative level of 1-100% the maximum color flux of  
the lighting fixture through control of each individual lighting element.

This is especially important for the flux of blue light (viz., 464nm). It  
should be noted that a lighting system with a shorter range of 3500-5000K for  
example can still satisfy the requirements to coordinate circadian rhythms by  
10 regulating output of blue light (specifically the flux of 464nm light). It is within the  
scope of the invention that a lighting device comprising at least three lighting  
elements of characteristic chromaticity illustrated in Figs. 13a-14b may be limited to  
the range of 3000-6000K for example based on the balance of lighting elements in  
the fixture. Furthermore, a lighting device comprising at least three lighting elements  
15 of the characteristic chromaticity illustrated in Figs. 13a-14b where each lighting  
device outputs at any flux level is within the scope of the present invention.

In one example, the circadian rhythm of a subject is regulated or affected by  
artificial light where the flux of blue light (specifically 464 nm) is adjusted through  
changes in color temperature, brightness, or both. This example teaches that even  
20 warm white light contains a quantity of blue light which can influence a circadian  
response, and that light of a constant color temperature can be modulated in intensity  
to induce a circadian response.

The present invention implements a prescriptive control of the blue light  
component of the overall white light emission. By way of example only, a  
25 combination of at least three lighting fixtures can be controlled whereby the total  
flux of blue light can be adjusted from a relative level of 1-100% the maximum blue  
flux of the lighting device through control of each individual lighting element.  
Therefore, for example, where three lighting fixtures emit white light at 20 lux, 200  
lux and 2000 lux, respectively, the blue light component for each fixture can be  
30 controlled at a 25% relative level, namely, 5 lux, 50 lux and 500 lux, respectively.

As shown in Figs. 15, a controller 299 executes operations within a fixture 319 by  
employing a closed loop feedback mechanism incorporating at least two spectrally  
unique sensors 300 and at least one lighting element 250/260 using at least three

channels 301. Means of external input 302 allows for the fixture to be dimmed or for its color conditions to be changed by applying a modulated duty cycle or by applying a pulse width modulation (PWM) signal to the channels or groups of lighting elements. In the case of high power LEDs suited for general illumination, other components 303  
5 such as amplifiers or drivers are necessary to amplify the PWM signals produced by the controller, however for illustration purposes, these components will be summarized as above. Elements enclosed by the dashed line 319 are components within a single fixture.

Similarly, the lighting elements 308 can be grouped or consolidated into one or  
10 more devices 305 such as a multi channel amplifier, multi channel driver, or other controller coupled with an analog to digital converter circuit before coupling with the controller 309. To those known in the art, it is apparent that there are several ways of multiplexing these channels, and illustrated within are a few common examples. In particular, Fig. 16 shows the configuration of Fig. 15 using dedicated amplifiers 303 for  
15 the three channels 301. Alternatively, a multi-channel amplifier 305 can be used as shown in Fig. 17.

As shown in Fig. 18, multiplexed devices such as lighting elements, sensors, amplifiers, and other devices may be combined on a common digital bus 310 as a means of interconnecting with a central controller using a variety of analog to digital  
20 converters, drivers, or controllers. A collection of sensors and lighting elements within close proximity can form an array 307 or individual closed loop when the said devices are connected to a common bus. The analog to digital converter circuit in Fig. 18 may comprise a microcontroller device capable of accepting a plurality of analog inputs and combining them on a common connection such as a digital interface, an I2C interface,  
25 or a serial interface.

For some types of optical sensors such as photodiodes, a transimpedance amplifier may be necessary to convert current to voltage for the controller to process feedback data. Fig 16 depicts sensors connected to singular transimpedance amps 500 which consist of a single current input and a single voltage output. Fig. 17, 18, & 19 depict  
30 sensors which are connected to a multi-channel transimpedance amplifier 507 which accepts multiple current inputs from sensors and outputs multiple voltages to the controller. To those skilled in the art, it is apparent that this multi-channel transimpedance amplifier can be combined with or interfaced to an analog to digital

converter to combine a plurality of voltage signals to a single digital interface such as I2C. This arrangement has not been explicitly illustrated.

Fig 19 shows that multiple arrays or collections of devices within common spatial regions can be combined on a common digital bus 315 and controller 318, forming multiple closed feedback loops 316, 317 within a singular fixture represented by a bounding dashed line 319 (or 319A).

Fig 20 shows the sensor activation sequence. Following the initialization step 320, channels 1, 2, and 3 are activated during steps 321, 323, 325, respectively, in sequence and the corresponding sensor data are recorded during recordation steps 322, 324 and 326. From data gathered, the color match function is executed at step 327 and the result is sent to the controller at step 328 to accurately operate the fixture at the correct color. Basically, the color match function (CMF) involves driving the lighting elements to the calibration point of the sensors. This can be achieved in various ways from manual changes to automated methods or a combination of both.

As mentioned previously, three unique spectral sensors (A, B and X) are in close proximity to the at least three channels 301 comprising a plurality of lighting elements (250). However, it should be understood that the number of sensors is not limited to three (hence, the sequence, A, B and X, with indicating an infinite number of sensors). In fact, it is within the broadest scope of the invention to include at least two sensors. Similarly, it should be understood that the number of channels is not limited to three (hence the sequence of 1, 2,  $\mu$ ). In fact, it is within the broadest scope of the invention to include at least three channels.

In this embodiment, a first group or channel of lighting elements is activated 330, illustrated by the Fig. 21 output chart with time on the x axis 331 and amplitude on the y axis 332. At this time, a corresponding set of inputs from the sensors is recorded, illustrated by voltages 333, 334, and 335 on the input chart in Fig. 23. A second group or channel of lighting elements is then activated 336 and another set of inputs 337 are recorded from the sensors. This process continues until all X channels are activated.

Fig. 23 illustrates the data available to the fixture upon completion of the calibration sequence described by Figs. 22-23. Columns 341, 342, 343, and 344, represent the data obtained from the short interval in which a single lighting element or collection of common elements is illuminated at the start up sequence. Column 344 represents values corresponding to the unique inputs obtained from the sensors after

applying a balanced duty cycle to each lighting element, or illuminating each element to balanced intensities. Values 345 are the initial condition (lifetime = 0 hours) balanced duty cycle voltages obtained from the sensors with a new lighting element or elements. This illustrated data is used by the controller and algorithms to illuminate a collection of lighting elements where the additive output corresponds to pre determined conditions.

As shown in Fig. 24, a serially linked digital network 350 (e.g., RS-485 or RS-232) may be used to control lighting elements 353 and a central control unit 351. This network can establish a strictly one way or two way communication between devices. In this embodiment, a typical lighting control network interfaces with another non-serial network such as a common Ethernet network 352 for accessing advanced features, configurations, and diagnostic information. The serially linked digital network 350 may use a digital protocol such as I2C, a serial protocol such as RS-485, RS-232, or a wireless protocol such as Zigbee or other RF signals.

Fig. 25 shows that such control networks can also incorporate other elements common to lighting systems such as light sensors 354 and user controls 355 such as switches. These devices are identified on the network as any other device with an address and defined input and or output channels, operating on a common communication protocol.

As shown in Fig. 26, this communication protocol may be transmitted across other common networks such as Ethernet or wireless networks using network adapters 360 to extend the reach of a control network or to simplify interconnection of single devices 361, 362 or groups of devices 363, 364. In this embodiment, a wired Ethernet network is illustrated in which adapters are employed to extend the reach of devices on the control network.

With a communications network in place linking multiple lighting fixtures, several time-color profiles can be assigned to one or more of these fixtures. In one embodiment, a simple schedule described in Fig. 27 is assigned to a group of lighting fixtures, in which the horizontal x axis 380 represents the time of day from 0 to 24 hours, and the vertical y axis 381 represents the correlated color temperature in degrees Kelvin. This profile gradually varies the correlated color temperature of the lighting fixtures over a period of 24 hours, illustrated by the solid line 382. Fig. 28 describes how brightness of a fixture may be changed throughout a 24 hour period where the horizontal x axis 383 represents the time of day from 0 to 24 hours, and the vertical y

axis 384 represents the perceived brightness of the fixture. The profiles described in Figs. 28-29 may be assigned independently of one another, and only represent one embodiment of the invention. Regarding schedules (e.g., as shown in Figs. 27-29), the time period may be variable, corresponding to a day (e.g., 24 hours), a portion of a day, defined by the lighting device as a function of input such as intensity or dimming level, or defined by an external controller as a function of input such as intensity or dimming level. In one embodiment, a dynamically changing brightness - color function is used in response to user input rather than a defined schedule. In this embodiment, the color temperature of the lighting fixtures is dynamically changed in real time in response to the user defined brightness of the fixture. The resultant behavior of this embodiment is meant to mimic the color - brightness behavior of an incandescent light bulb being dimmed.

It should be noted that the communication system:

- may comprise methods to program cues and or schedules;
- may be analog in nature and wherein changes in an input voltage denote a change in cue or lighting schedule;
- may include a digital connection comprising serialized data bits or packets coordinating fixtures;
- may comprise an external control device and tree structure or daisy chain structure;
- may comprise communication of cue changes or activation of conditions programmed into fixtures;
- may comprise communication of specific colorimetric or feedback loop data;
- may comprise a communication of pulse width modulation parameters; or
- may comprise a wireless mesh network exhibiting distributed structure or top down structure.

In another embodiment described by Fig. 29, brightness, color temperature, and time are assigned graphically using an interface consisting of sliders 388, 389 and zones 390, 391, 392. Profiles containing time dependent information on brightness and color temperature may be saved in a digital format and modified by the user.

Settings, profiles, preferences, and other functions such as off and on may be controlled using a push button interface installed in an interior. Fig. 30 describes one such interface 395 where the user interacts with the system using a collection of push buttons. Similarly, these push buttons may be arranged on a touch sensitive display



device capable of dynamically changing to present the user with additional options 396. Interactions with the control panels described in Fig. 30 results in dynamic changes to the system which may include time, color, and brightness autonomous changes requiring no further input.

5           Fig. 31 describes an embodiment in which a handheld computing device such as a phone, PDA, or notebook computer 400 makes a common connection 401 with an adapter 402 in the communication network common to the lighting elements 403 and central controller 404. In this embodiment, a user is able to make changes to the lighting network affecting time dependent functions of color and brightness of the lighting  
10       fixtures.

          Fig. 32 describes several user options available to a handheld computing device 409, where 410, 411, and 412 are three such control panels which can be displayed on the integrated display device in the handheld computing device 409. User inputs on the handheld device through control panels described in Fig. 32 can have a time dependent  
15       change on brightness and color of the lighting elements in the control network.

          Fig. 33 depicts how a desktop computer can be used to interface with a lighting control network. In this embodiment, the central control unit 421 can store settings defined by the computer device 420 through a graphical user interface where a user modifies settings affecting brightness, color, and time of lighting characteristics produced by lighting fixtures 424 in the network using human input devices such as a  
20       keyboard 423 and mouse 422. In this embodiment, the computer is necessary only to apply settings to the control unit 421, and in another such embodiment, the computer 420 directly controls the lighting elements 424 using the control unit 421 as a network translator.

25           Fig. 34 describes three user control panels in the graphical user interface. Users modify parameters in the interface using a human interface device such as a mouse or keyboard. Display screen 450 depicts how the spatial position of a lighting fixture 449 may be defined in relation to a room floor plan 451 and a window 452. Display screen 453 depicts a method by which the user can make a selection of lighting fixtures by  
30       drawing an enclosed shape 454 on the floor plan 455. Panel 456 describes the interface using sliders 457 and zones 458 used to modify color and brightness schedules.

          Fig. 35 depicts how the present invention controls the sensor gain setting. In particular, Fig. 35 depicts a single transimpedance amplifier circuit unit 500 which is

used to convert the current output of a photodiode sensor 501 into a voltage 506 suitable for interfacing to a controller. This transimpedance amplifier circuit operates using a constant reference voltage 502, an OP Amp 503, a resistor 504 (e.g., a potentiometer, MTI04C transimpedance amplifier that uses an internal variable resistor, etc.), and a capacitor 505. The 504 resistance determines the input current 501 sensitivity and may be held constant or can be changed to accommodate a wide dynamic range of input current 501. The capacitor 505 is selected to properly compensate the input capacitance of the photosensor. The resistor 504 may be internal to the amplifier component 500, in which case its value is fixed; it may consist multiple internal resistors to the component which are activated by pins on the device, or this resistor may be located external to the amplifier 500, in which case it may be variable.

Fig. 36 depicts a similar transimpedance amplifier to Fig. 35 but comprises multiple input currents 508 and multiple output voltages 509. This multi channel transimpedance amplifier 507 operates similarly to the amplifier described in Fig 35, employing multiple OP amps and resistors 510 with one singular reference voltage 511.

Since the light fixture's brightness level is variable, the light falling on the sensor may not be within the transimpedance amplifier's current threshold. This is why it is useful to change the resistor 504 resistance value to properly suit the sensing range of the fixture. Fig 37 relates the light fixture's intensity given by series 517 ranging in 20%-100% relative brightness to the required resistance 516 in the transimpedance amplifier circuit necessary to resolve a voltage 515 to properly acquire optical feedback. For example, at 100% relative brightness, a given lighting channel's luminance may activate a given sensor, providing a current from the photodiode on the order of 1-10 $\mu$ A. In order for the transimpedance amplifier to resolve this range of current, the resistance of resistor 504 must be on the order of 100K $\Omega$ . In another case, the lighting fixture is dimmed to 20%, providing only 0.1 $\mu$ A of current for the transimpedance amplifier 500. If resistor 504 is fixed at 100K $\Omega$ , the voltage output 506 of the amplifier will be at a constant minimum 516, providing no useful data for feedback. In this case, it is necessary to change the resistance of resistor 504 to ~5M $\Omega$  to achieve sensitivity in the 0.1-0.05  $\mu$ A current range.

By way of example only, one application of the system/method of the present invention is the generation of an enriched light at 460nm at an irradiance of 30 $\mu$ W/cm<sup>2</sup> for use in treating clinical jaundice in newborns. Approximately 60% of all newborns

become clinically-jaundiced sometime during the first week of life and phototherapy is indicated to help the neonatal liver clear bilirubin from their blood, as recommended by the Academy of Pediatrics.

Another exemplary application of the system/method of the present invention is the generation of an enriched light of 290nm-315nm to aid in Vitamin D production. This is an issue especially in the winter months as many people do not go outdoors and receive adequate sunlight exposure. This is also becoming an issue in the summer months too, as many elderly are staying out of the sun and closing their shades to save on energy costs. Seasonal Affective Disorder is usually treated with a light therapy of as much as 10,000 lux at 30 inches from the body for at least 30 minutes per day. In contrast, the light box therapy used currently is more focused on total lux versus the quality of the light to match a full sunlight spectrum.

Thus, it should be understood that another exemplary application of the system/method of the present invention is Circadian Rhythm manipulation. For example, the present invention can implement Circadian Rhythm manipulation for the following individuals or scenarios:

- military application of training soldiers for 36-hour days;
- weaponization (intentional disorientation of enemy combatants' biorhythms);
- astronauts (for off-Earth environments or unintended return-to-Earth environments);
- this would include Lunar or Mars missions, or employing the system/method at 1000 atmospheres below the ocean surface; the color temperature may be strange to compensate for deep space/Mars/ocean attenuation/or generally odd locally available light;
- other military or aerospace applications which utilize different color spaces, e.g., conditioning Mars astronauts and training to work in constant 1800K Mars atmosphere light while maintaining Circadian Rhythm balance, or conditioning soldiers for 36 hour day deployments and back to 24 hour off-duty cycles. By way of example only, Fig. 38 depicts an exemplary schedule where the system/method of the present invention is utilized in a Circadian Rhythm manipulation. In particular, Fig. 38 describes another embodiment, in which the lighting system is used to adjust a subject to a 36-hour day, rather than a 24-hour day. In this embodiment, cycles of variable time periods are inputted end to end into the lighting system, beginning with a 24 hour, 525 daily schedule. The 24 hour cycles are followed by multiple 526 conditioning cycles, ranging

between 24 and 36 hours, comprising the conditioning period 526. After the subjects have been appropriately conditioned to a 36 hour day, the deployment period 527 begins, which consists a user-defined length in number of cycles. In order to acclimate a subject back to a natural 24 hour 529 daily schedule, a recovery period 529 is defined by the user.

It should be noted that the lighting elements discussed above may comprise chip-type light emitting diodes (LEDs), packaged LED emitters, arrays of chip type LED emitters incorporated into a single package, or collections of packaged LED emitters attached to a common board or light engine. These LED emitters may be coated with materials intended to convert high frequency light into low frequency broad spectrum light, such as YAG:Ce phosphors, phosphor coatings, phosphor films, or lenses containing phosphor dispersions. Additionally, quantum dot photonic crystals, photonic nanocrystals, or semiconducting nanoparticles may be incorporated into lighting elements by means of coating, film, or filled lens material to convert high frequency light into lower frequency light. By extension, lighting elements may incorporate a blend of lumiphors or conversion materials, where each component converts light to a unique lower frequency color. More than one lumiphor may be incorporated into lighting devices where lumiphors are applied in sequence to different regions of the light emitting component, analogous to sub pixels on a video display. Lighting elements may also comprise devices employing organic semiconducting materials, such as organic light emitting diodes (OLEDs), or phosphorescent materials which emit either white or narrow band light in specific regions in the spectrum.

It should be further noted that intensity of channels or groups of lighting elements may be changed by pulse width modulation, current modulation, or other means of duty cycle modulation.

The sensors identified in Figs. 16-24 may comprise charge coupled devices (CCD), ceramic metal oxide sensors (CMOS), phototransistors, or photodiodes. Each sensor may be an assembly or collection of multiple such devices employing visible filters or neutral density filters at the optical aperture of the sensors. Additionally, this sensor may be a chip type device incorporating multiple such sensors and color filters in a single package. Arrays packaged in this manner are often referred to as "color sensors" and may incorporate a means of changing gain settings to modify the luminous flux – output characteristics of the device via pin jumper settings. Sensors, sensor arrays, or

sensor assemblies communicate with the controller via an analog or digital interface. The sensor or sensors may employ a transimpedance circuit to convert discrete current outputs to voltages and an integrated analog to digital converter circuit to combine the outputs of multiple sensors on a single digital or serial interface. Example components include:

- a. ADJD-S313-QR999 digital RGB 7 bit color sensor from Avago Technologies;
- b. HDJD-S722-QR999 analog RGB color sensor from Avago Technologies;
- c. Hamamatsu S10170 3 – channel photodiode;
- d. TAOS TCS230 Light to Frequency converter

It should be further noted that it is within the broadest scope of the present invention to include various types of optical sensors and optical sensor output formats. For example, the optical sensors of the present invention may include analog optical sensors that output voltages or digital sensors that output data and/or frequency. Thus, optical sensors that output chromaticity coordinates as opposed to voltage, frequency or other output formats (e.g., other data) are all within the broadest scope of the invention. This also includes various sensor processing mechanisms such as voltage/frequency/current signals that are representative of optical data that can be correlated with known optical data (e.g., via look-up tables or other correlation methods).

It should also be noted that although the preferred system and method of the present invention utilize feedback control, it is within the broadest scope of the present invention to include a light fixture system or light fixture method that uses no feedback control to artificially generate the daylight locus.

It should be further noted that it is within the broadest scope of the present invention to include the use of the more recent CIE 1960 chromaticity diagram, in addition to the CIE 1931 chromaticity diagram mentioned previously, with regard to the system/method operation of the present invention.

While the invention has been described in detail and with reference to specific examples thereof, it will be apparent to one skilled in the art that various changes and modifications can be made therein without departing from the spirit and scope thereof.

## CLAIMS

## WHAT IS CLAIMED IS:

1. A system for artificially generating sunlight in accordance with a daytime locus using spectral characteristics that resembles sunlight, said system automatically  
5 controlling at least one lighting fixture substantially along said daytime locus to generate said artificial sunlight.
2. The system of Claim 1 wherein said system automatically changes brightness levels and color levels of a plurality of lighting element channels within said at least one lighting fixture which generate broad spectrum white light of color temperatures from  
10 1800K to 6500K in accordance with a user-selected input.
3. The system of Claim 2 wherein said system comprises:  
at least two light sensors that detect the light emitted from  
said plurality of lighting element channels and generate respective  
signals of said detected light; and  
15 a controller coupled to said plurality of lighting element channels and to said at least two light sensors, said controller using said respective signals of said detected light to drive said plurality of lighting element channels, said controller activating a color match algorithm for automatically creating respective drive signals for said plurality of  
20 lighting elements, said drive signals automatically varying a brightness level and a color level for each of said plurality of lighting element channels.
4. The system of Claim 3 wherein said plurality of lighting element channels comprises at least three lighting element channels for controlling a color balance of said  
25 at least three lighting element channels.
5. The system of Claim 4 wherein each one of said at least three lighting element channels comprises at least one lighting element.
6. The system of Claim 5 wherein said at least three lighting element channels uses white lighting elements on two of said at least three lighting element channels and  
30 uses amber lighting elements on the other one of said at least three lighting element channels.
7. The system of Claim 6 wherein said artificially generated sunlight by said system is defined within an XY chromaticity plane having x coordinates and y

coordinates, and wherein each of said at least three lighting element channels comprises a region within said XY chromaticity plane:

a first region of said at least three channels is defined by x and y coordinates (0.28, 0.28), (0.27, 0.30), (0.30, 0.33) and (0.31, 0.30);

5 a second region of said at least three channels is defined by x and y coordinates (0.34, 0.34), (0.34, 0.38), (0.43, 0.42) and (0.43, 0.39); and

a third region of said at least three channels is defined by x and y coordinates (0.59, 0.40), (0.61, 0.39), (0.54, 0.43) and (0.55, 10 0.45).

8. The system of Claim 5 wherein said at least three lighting element channels comprises four lighting element channels and wherein said four lighting element channels use white lighting elements on three of said four lighting element channels and use amber lighting elements on the other one of said four lighting element channels.

15 9. The system of Claim 8 wherein said artificially generated sunlight by said system is defined within an XY chromaticity plane having x coordinates and y coordinates, and wherein each of said four lighting element channels comprises a region within said XY chromaticity plane:

a first region of said four channels is defined by x and y 20 coordinates (0.28, 0.28), (0.27, 0.30), (0.30, 0.33) and (0.31, 0.30);

a second region of said four channels is defined by x and y coordinates (0.32, 0.33), (0.32, 0.34), (0.35, 0.36) and (0.35, 0.37);

a third region of said four channels is defined by x and y coordinates (0.41, 0.39), (0.41, 0.41), (0.48, 0.43) and (0.47, 0.41);

25 and

a fourth region of said four channels is defined by x and y coordinates (0.59, 0.40), (0.61, 0.39), (0.54, 0.43) and (0.55, 0.45); and

10. The system of Claim 3 wherein each of said at least two light sensors is 30 associated with a transimpedance amplifier whose sensitivity is automatically controlled by said controller for compensating for variation in brightness levels of said lighting fixture.

11. The system of Claim 2 wherein said system automatically changes said brightness levels and color levels based on a user dimming level input.

12. The system of Claim 11 wherein said user dimming level input further comprises a user color temperature input.

5        13. The system of Claim 2 wherein said system automatically changes said brightness levels and color levels based on the time of day.

14. The system of Claim 2 wherein said system automatically changes said brightness levels and color levels based on a geographic location.

10       15. The system of Claim 2 wherein said system automatically changes said brightness levels and color levels based on a desired circadian response.

16. The system of Claim 2 said system automatically changes said brightness levels and color levels based on a user input pertaining to activity from the group of activities including sleeping, working, studying, eating and resting.

15       17. The system of Claim 2 wherein said system automatically changes said brightness levels and color levels based on an angle of the sun.

18. The system of Claim 1 wherein said system can adjust said daytime locus to periods of time other than a 24 hour clock depending upon an application for artificially generating sunlight.

20       19. A method for artificially generating sunlight in accordance with a daytime locus using spectral characteristics that resembles sunlight, said method comprising:

providing a plurality of channels of lighting elements;

activating said plurality of channels to generate a composite light mixture;

detecting said composite light mixture; and

25       controlling said plurality of channels of lighting elements based on said detected composite light mixture to generate artificial sunlight along said daytime locus.

30       20. The method of Claim 19 wherein said step of controlling said plurality of channels of lighting elements comprises changing brightness levels and color levels of said plurality channels of lighting elements for generating broad spectrum white light of color temperatures from 1800K to 6500K in accordance with a user-selected input.



21. The method of Claim 20 wherein said step of detecting said composite light mixture comprises providing at least two light sensors that detect the composite light mixture and which generate respective signals of said detected light.

22. The method of Claim 21 wherein said step of controlling said plurality of  
5 channels comprises coupling a controller to said plurality of channels of lighting elements and to said at least two light sensors and wherein said controller uses said respective signals of said detected light to drive said plurality of channels of lighting elements.

23. The method of Claim 22 wherein said step of controlling said plurality of  
10 channels further comprises said controller activating a color match algorithm for automatically creating respective drive signals for said plurality of channels of lighting elements and varying a brightness level and a color level for each of said plurality of channels of lighting elements.

24. The method of Claim 23 wherein said plurality of channels of lighting  
15 elements comprises at least three lighting element channels for controlling a color balance of said at least three lighting element channels.

25. The method of Claim 24 wherein each one of said at least three lighting element channels comprises at least one lighting element.

26. The method of Claim 25 wherein said step of providing at least three  
20 lighting element channels comprises using white lighting elements on two of said at least three lighting element channels and using amber lighting elements on the other one of said at least three lighting elements.

27. The method of Claim 26 wherein said artificially generated sunlight is defined within an XY chromaticity plane having x coordinates and y coordinates, and  
25 wherein each of said at least three lighting element channels comprises a region within said XY chromaticity plane and wherein said step of providing at least three lighting element channels comprises selecting lighting elements of the following XY chromaticity plane regions:

a first region of said at least three channels is defined by x and  
30 y coordinates (0.30, 0.33), (0.35, 0.37), (0.35, 0.34) and (0.31, 0.31);

a second region of said at least three channels is defined by x and y coordinates (0.37, 0.39), (0.48, 0.43), (0.46, 0.39) and (0.36, 0.35); and

a third region of said at least three channels is defined by x and y coordinates (0.54, 0.42), (0.55, 0.45), (0.60, 0.40) and (0.57, 0.40).

5 28. The method of Claim 25 wherein said step of providing at least three lighting element channels comprises using four lighting element channels and wherein said four lighting element channels comprise white lighting elements on two of said at least three lighting element channels and using amber lighting elements on the other one of said at least three lighting elements.

10 29. The method of Claim 28 wherein said artificially generated sunlight is defined within an XY chromaticity plane having x coordinates and y coordinates, and wherein each of said four lighting element channels comprises a region within said XY chromaticity plane and wherein said step of providing four lighting element channels comprises selecting lighting elements of the following XY chromaticity plane regions:

15 a first region of said four channels is defined by x and y coordinates (0.30, 0.33), (0.35, 0.37), (0.35, 0.34) and (0.31, 0.31);

a second region of said four channels is defined by x and y coordinates (0.35, 0.37), (0.41, 0.41), (0.40, 0.37) and (0.35, 0.34);

20 a third region of said four channels is defined by x and y coordinates (0.41, 0.41), (0.48, 0.43), (0.46, 0.39) and (0.40, 0.37); and

a fourth region of said four channels is defined by x and y coordinates (0.54, 0.42), (0.55, 0.45), (0.60, 0.40) and (0.57, 0.40).

25 30. The method of Claim 22 wherein said step of detecting said composite light mixture comprises associating a transimpedance amplifier with each of said at least two light sensors and automatically controlling the sensitivity of said amplifier by said controller for compensating for variation in brightness levels of said lighting fixture.

31. The method of Claim 20 wherein said step of controlling said plurality of channels of lighting elements comprises using a dimming level input.

30 32. The method of Claim 31 wherein said step of using a dimming level input further comprises using a color temperature input.

33. The method of Claim 20 wherein said step of controlling said plurality of channels of lighting elements comprises changing said brightness levels and color levels based on the time of day.

34. The method of Claim 20 wherein said step of controlling said plurality of channels of lighting elements comprises changing said brightness levels and color levels based on a geographic location.

5 35. The method of Claim 20 wherein said step of controlling said plurality of channels of lighting elements comprises changing said brightness levels and color levels based on a desired circadian response.

36. The method of Claim 20 wherein said step of controlling said plurality of channels of lighting elements comprises changing said brightness levels and color levels based on a user input pertaining to activity from the group of activities  
10 including sleeping, working, studying, eating and resting.

37. The method of Claim 20 wherein said wherein said step of controlling said plurality of channels of lighting elements comprises changing said brightness levels and color levels based on an angle of the sun.

38. The method of Claim 19 wherein said step of controlling said plurality of  
15 channels comprising adjusting said daytime locus to periods of time other than a 24 hour clock depending upon an application for artificially generating sunlight.

39. The method of Claim 20 wherein said step of automatically changing brightness levels and color levels comprises coordinating precise brightness and color schedules among said at least two lighting elements while maintaining a high color  
20 reliability.

40. An artificial sunlight system, said system comprising a lighting fixture whose light output is automatically controlled to reduce the effects of, or treat, one of the group of circadium rhythm disorders, shift work dysfunction and seasonal affective disorder by operating along a daytime locus to provide compensating artificial sunlight.

25 41. A method for artificially generating sunlight in accordance with a daytime locus using spectral characteristics that resembles sunlight, said method comprising:

providing a plurality of channels of lighting elements;

activating said plurality of channels to generate a composite

light mixture;

30 detecting said composite light mixture; and

controlling said plurality of channels of lighting elements based on said detected composite light mixture to generate artificial sunlight along said daytime locus for reducing the effects of, or treat, one of the group of circadium rhythm disorders, shift

work dysfunction and seasonal affective disorder by operating along the daytime locus to provide compensating artificial sunlight.

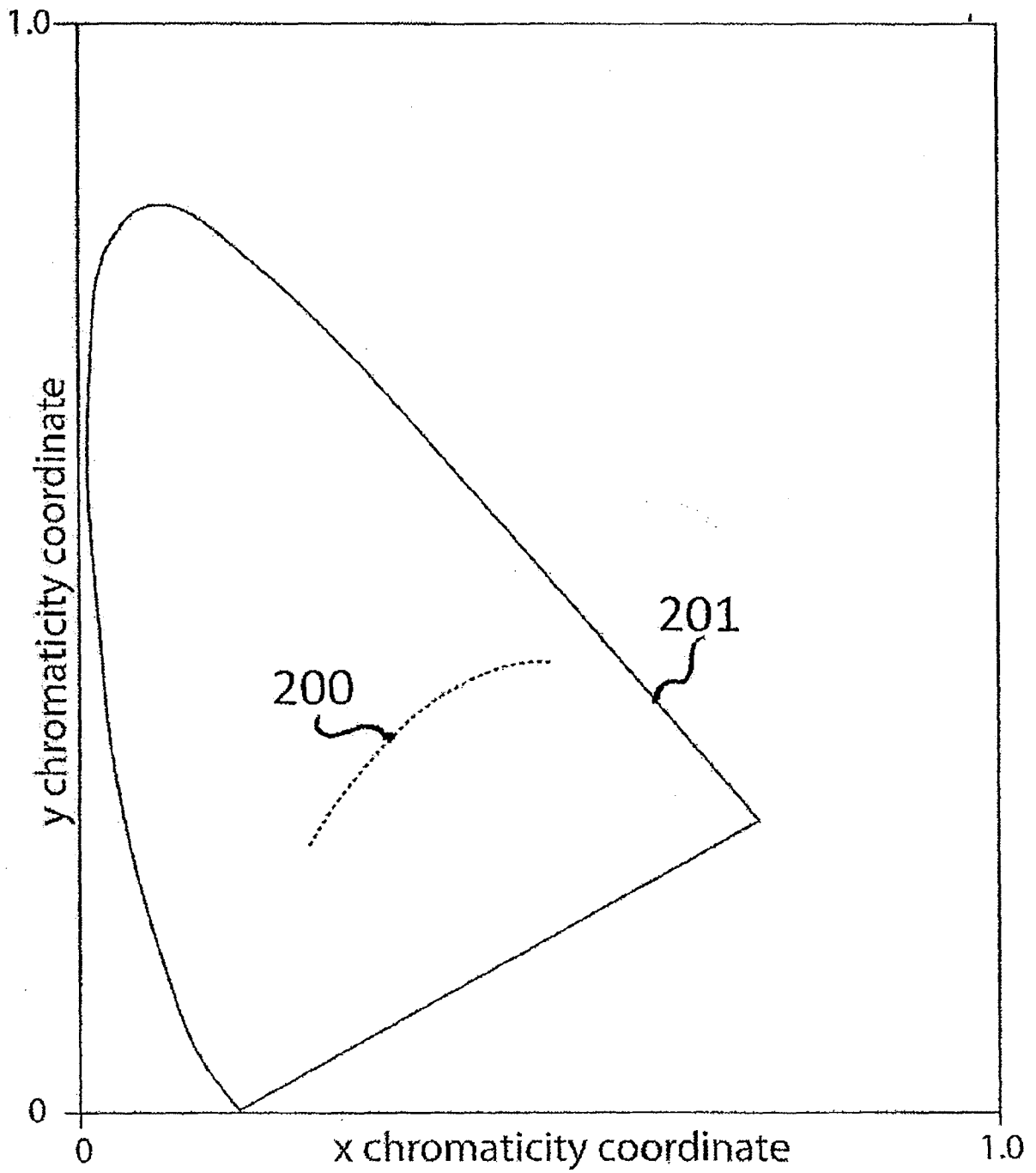
42. A system for artificially generating sunlight in accordance with a daytime locus using spectral characteristics that resembles sunlight, said system automatically  
5 controlling at least one lighting fixture substantially along said daytime locus to generate said artificial sunlight, said system automatically changing brightness levels and color levels of a plurality of lighting element channels within said at least one lighting fixture which generate broad spectrum white light of color temperatures from 1800K to 6500K in accordance with a user-selected input, said system controlling a  
10 total flux of blue light from a relative level of 1 to 100% of a maximum blue light flux within said broad spectrum white light.

43. A method for artificially generating sunlight in accordance with a daytime locus using spectral characteristics that resembles sunlight, said method comprising:  
providing a plurality of channels of lighting elements;  
15 activating said plurality of channels to generate a composite light mixture;  
detecting said composite light mixture;  
controlling a total flux of blue light which can be adjusted from a relative level of 1 to 100% of a maximum blue light flux of  
20 said composite light mixture; and  
controlling said plurality of channels of lighting elements based on said detected composite light mixture to generate artificial sunlight along said daytime locus having a broad spectrum white light of color temperatures from 1800K to 6500K.

25

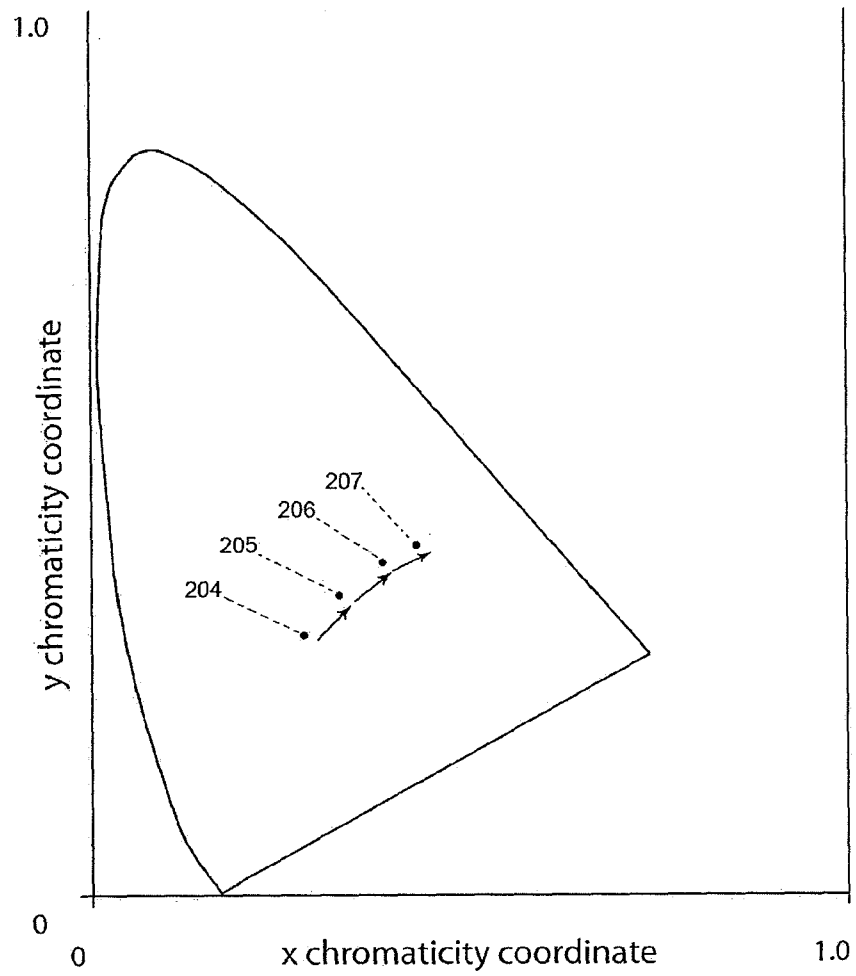
1/30

Fig 1



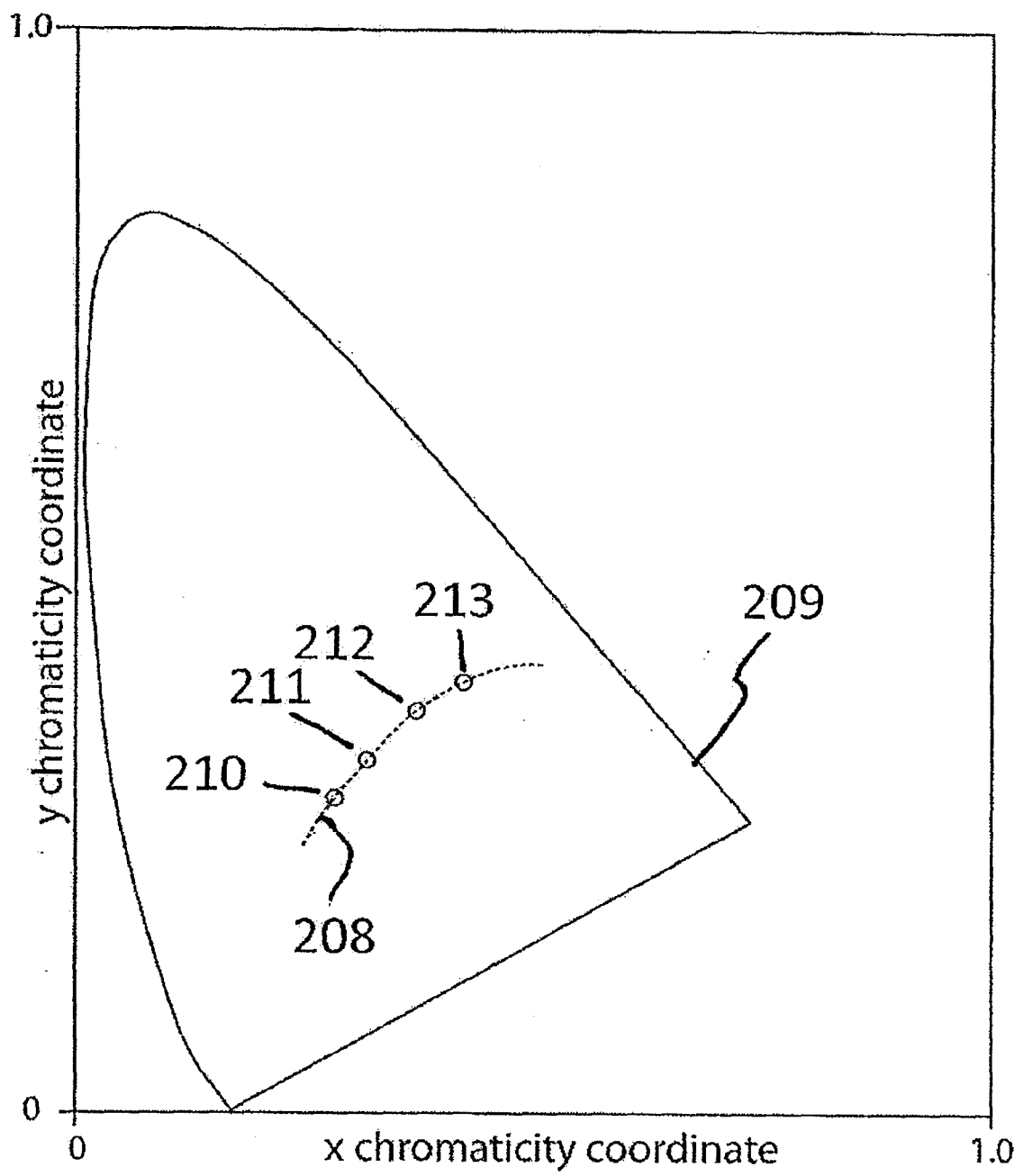
2/30

Fig 1b



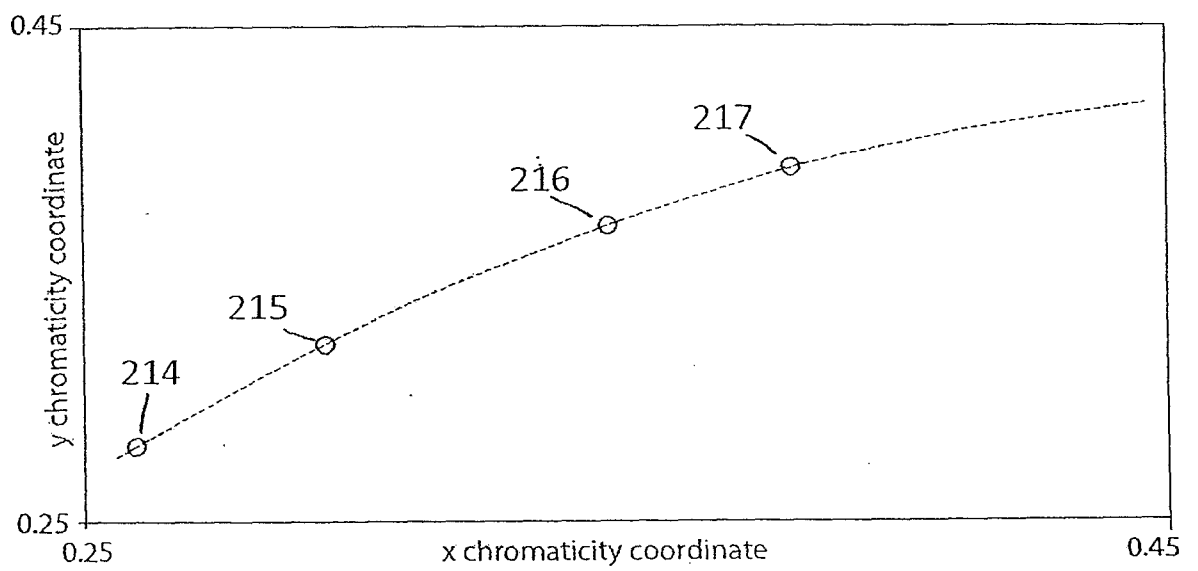
3/30

Fig 2



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Fig 3





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Fig 4

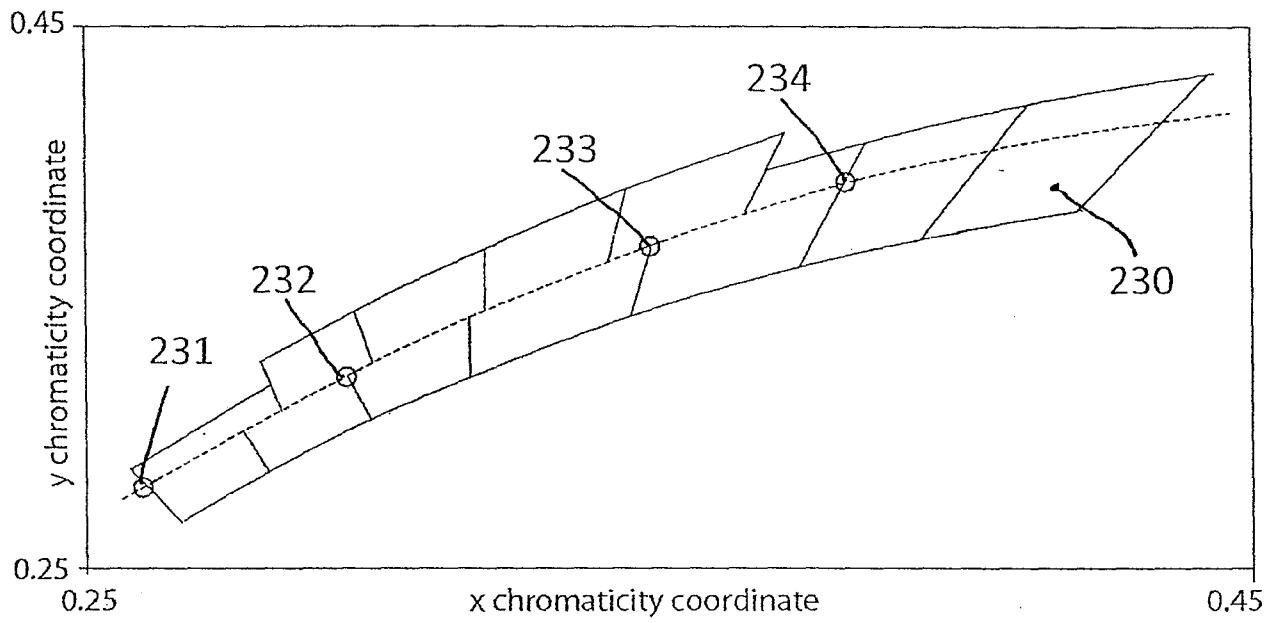
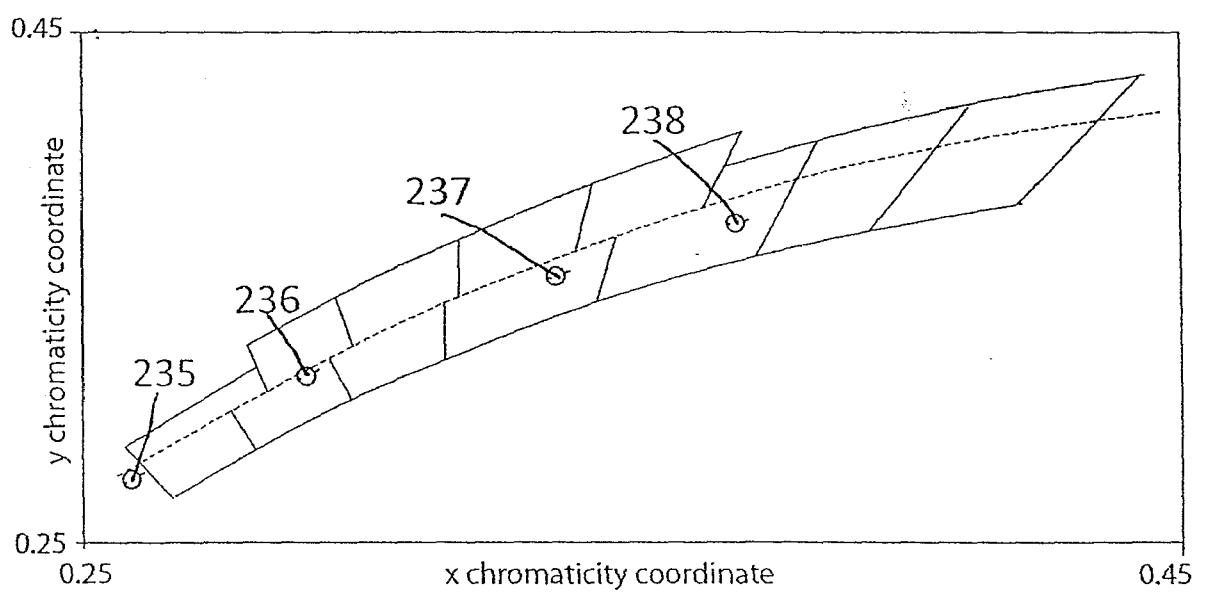
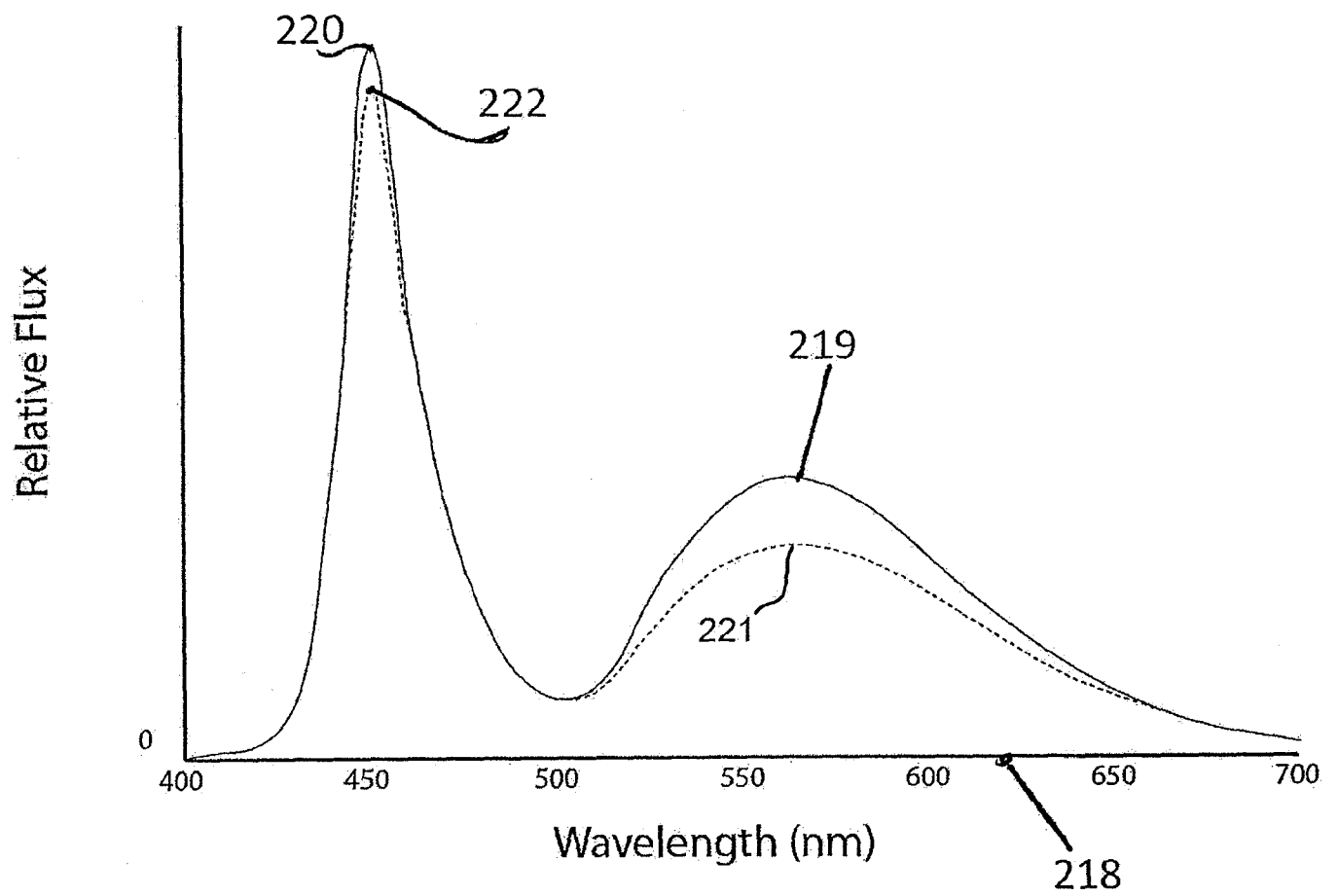


Fig 5



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Fig 6



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Fig 7

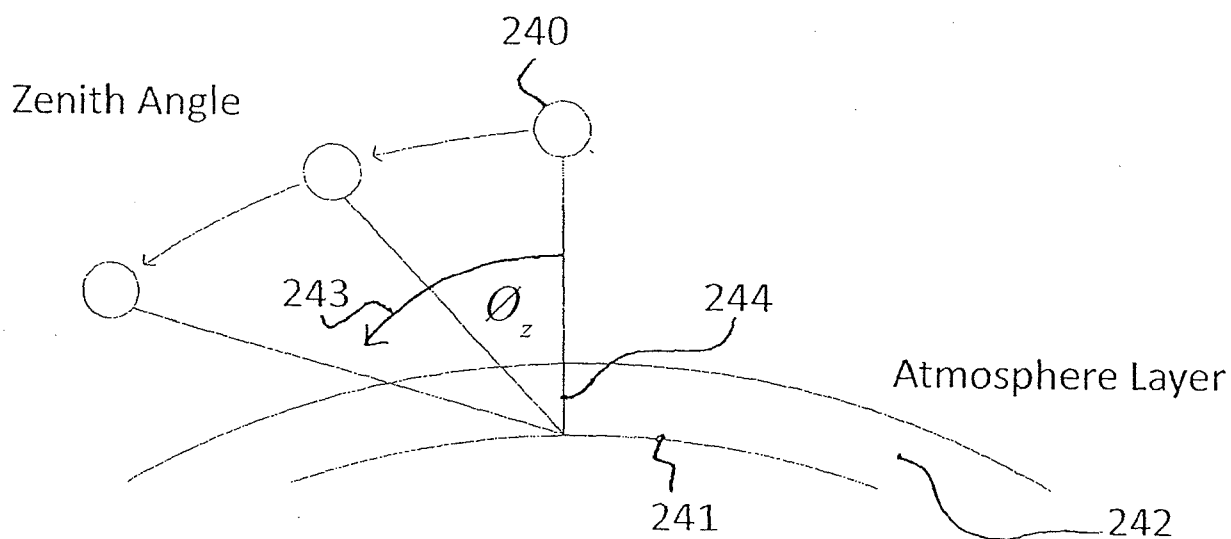


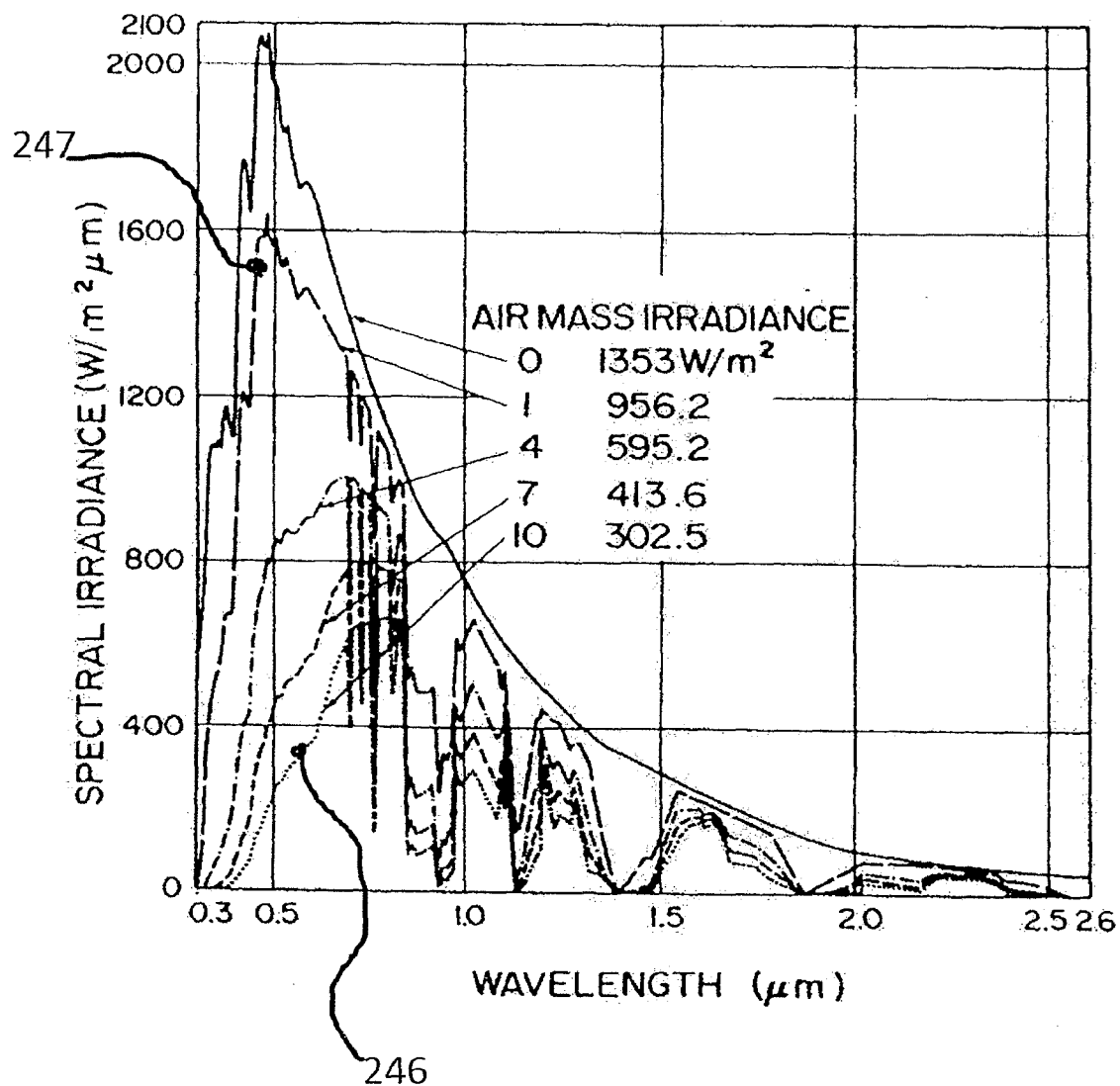
Fig 8

$$\text{air mass} = \frac{1}{\cos \theta_z + 0.50572(96.07995 - \theta_z)^{-1.6364}}$$

Diagram illustrating the equation for air mass. The equation is shown with labels 245, 246, and 246 pointing to the terms in the denominator.

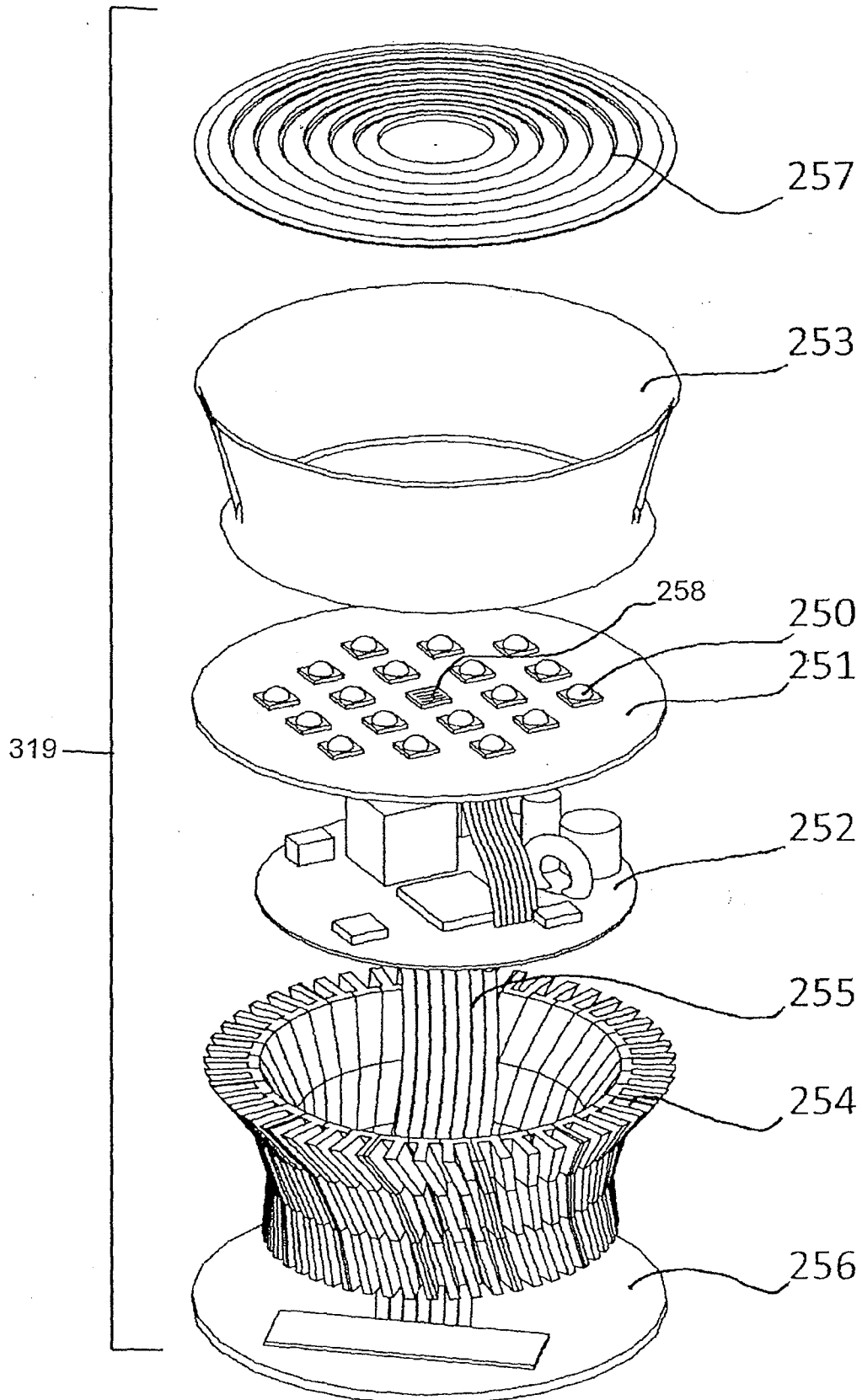
8/30

Fig 9



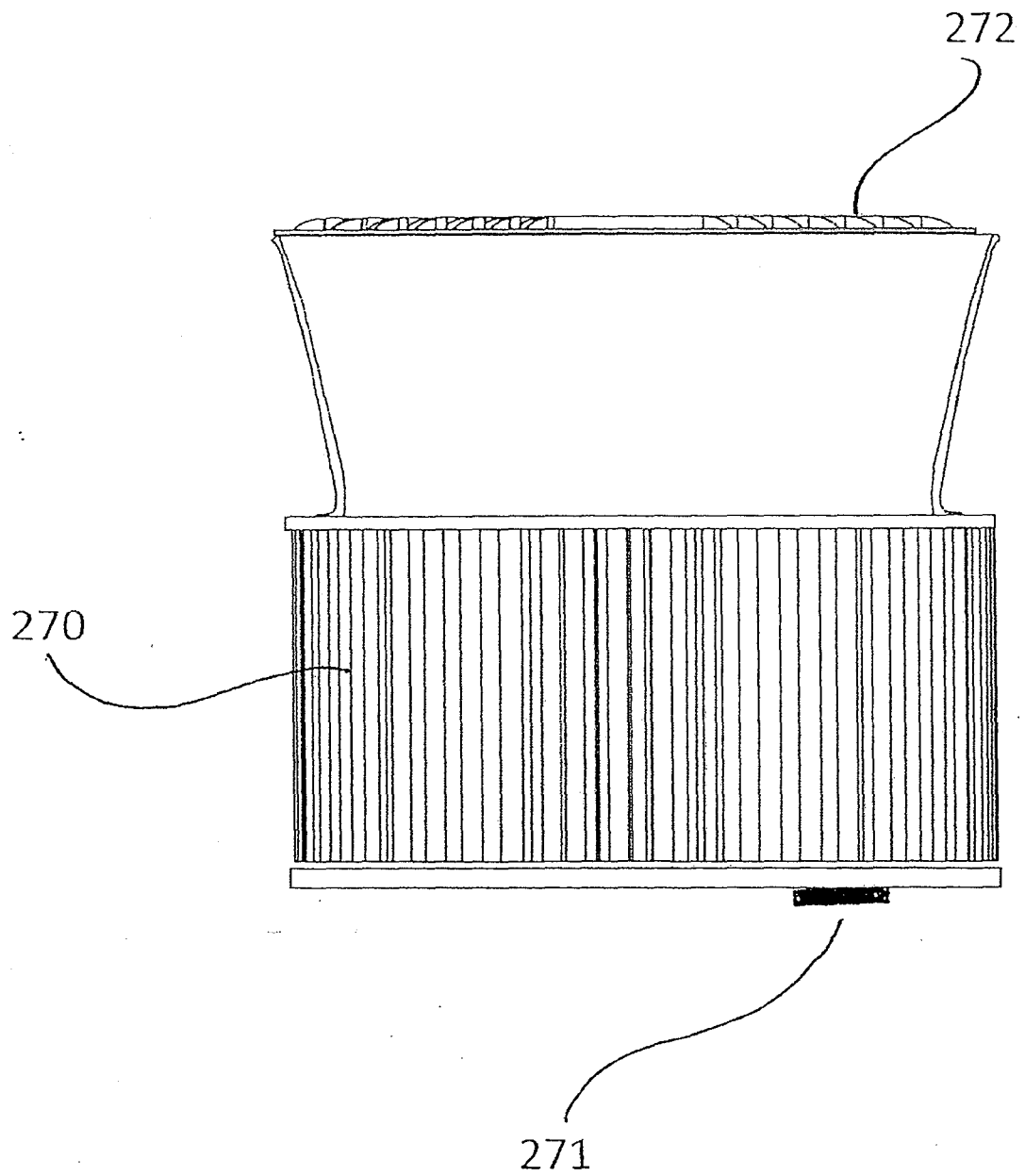
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Fig 10



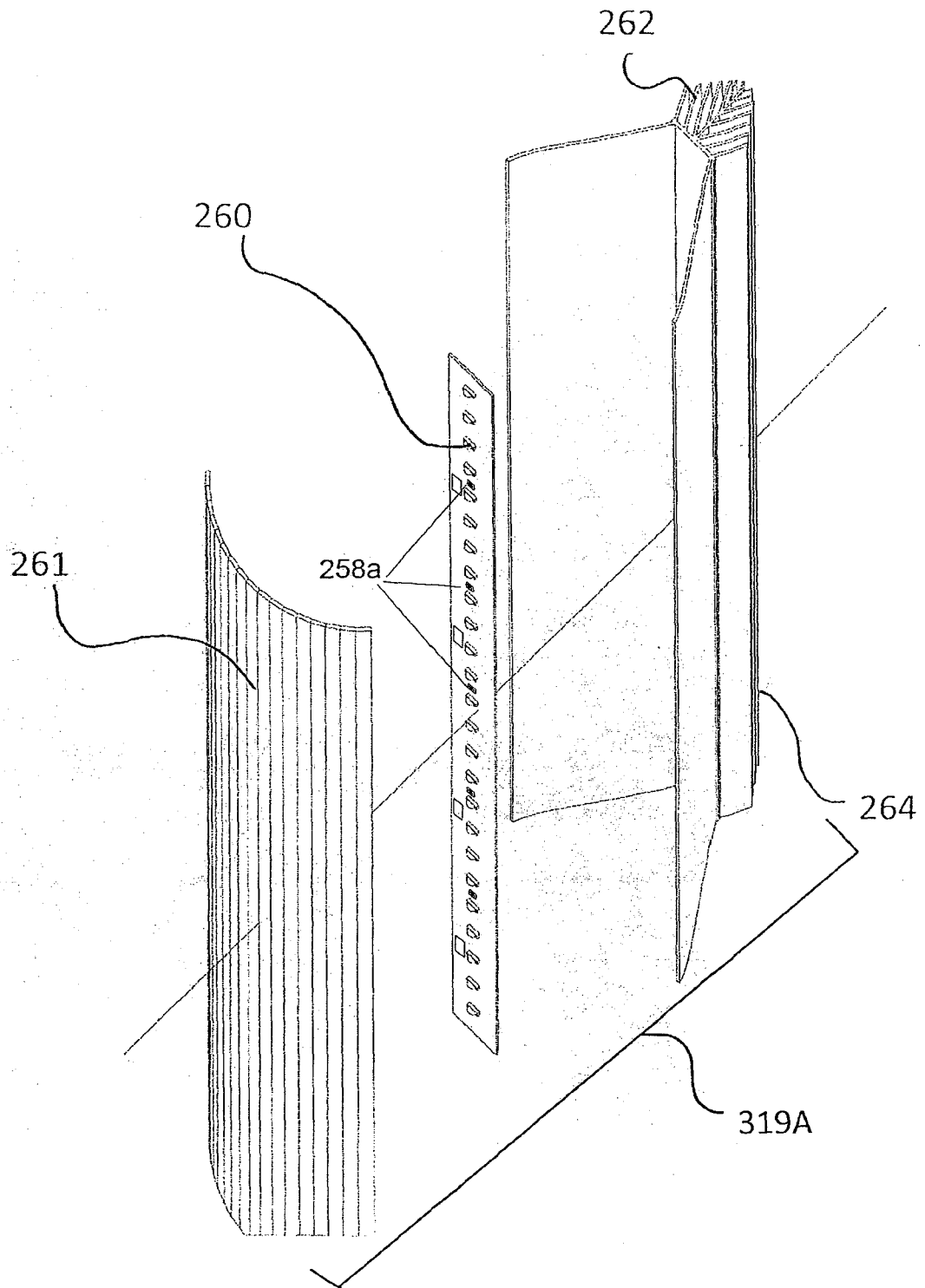
10/30

Fig 11



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Fig 12



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Fig 13a

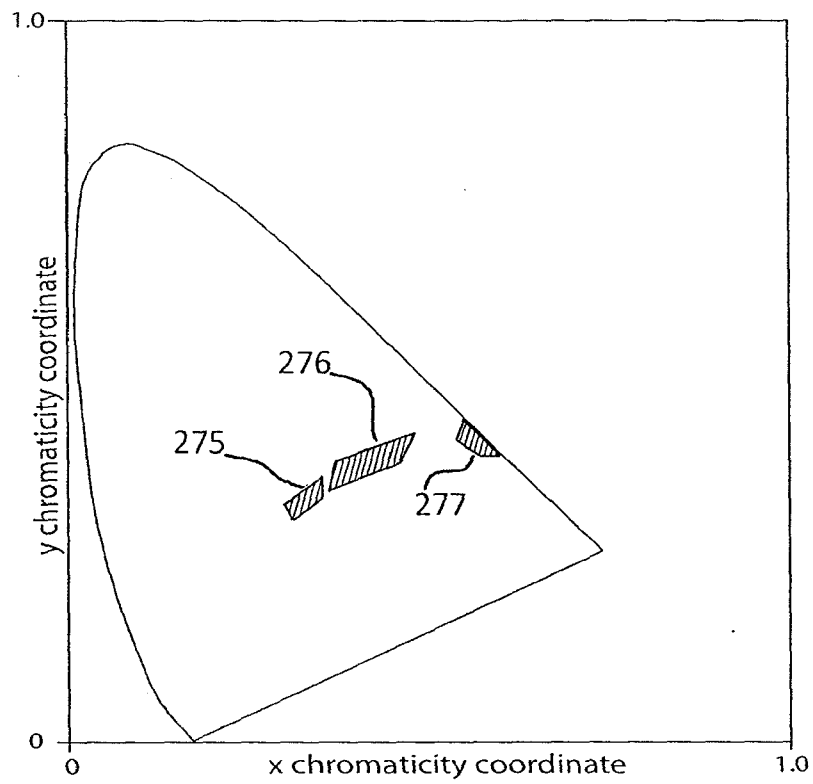
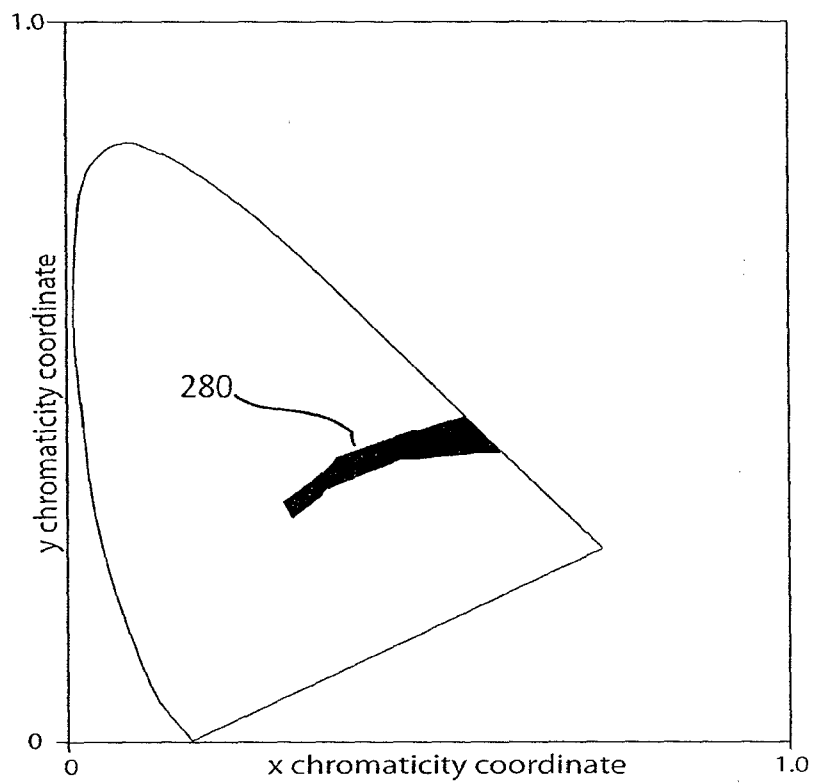


Fig 13b





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Fig 14a

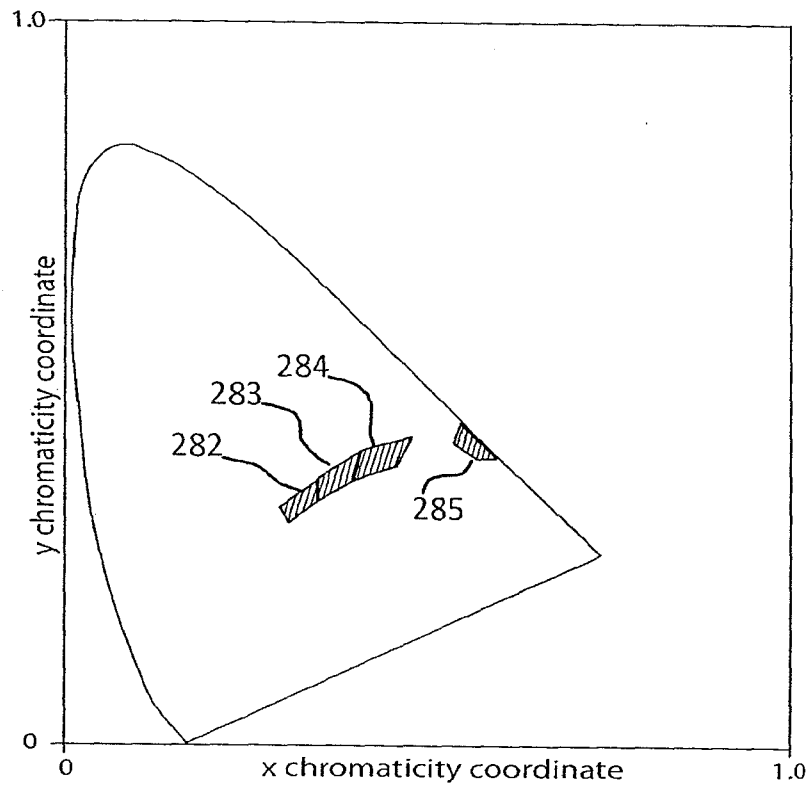
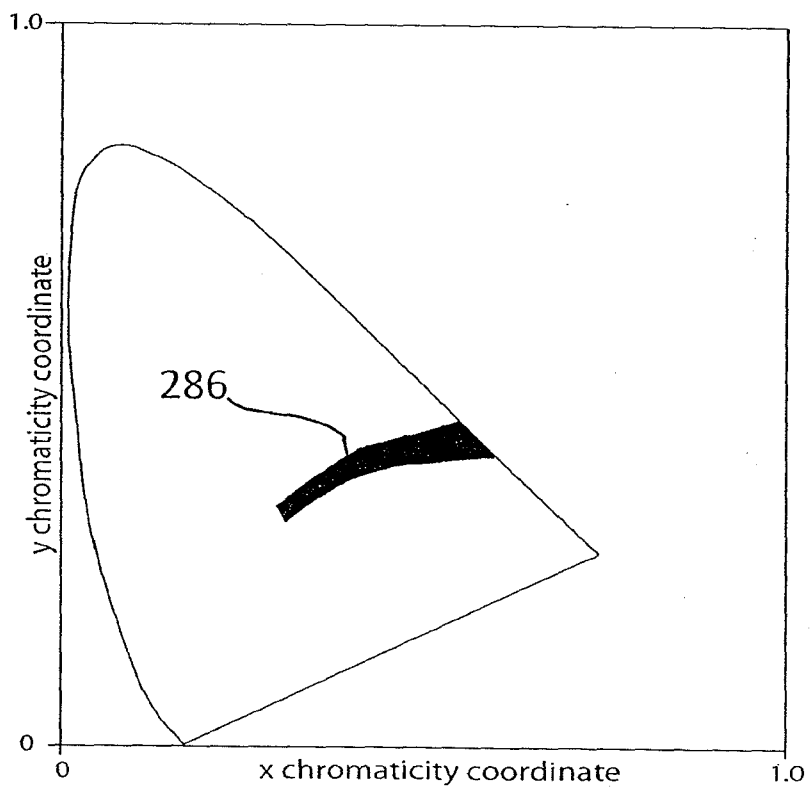


Fig 14b



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Fig 15

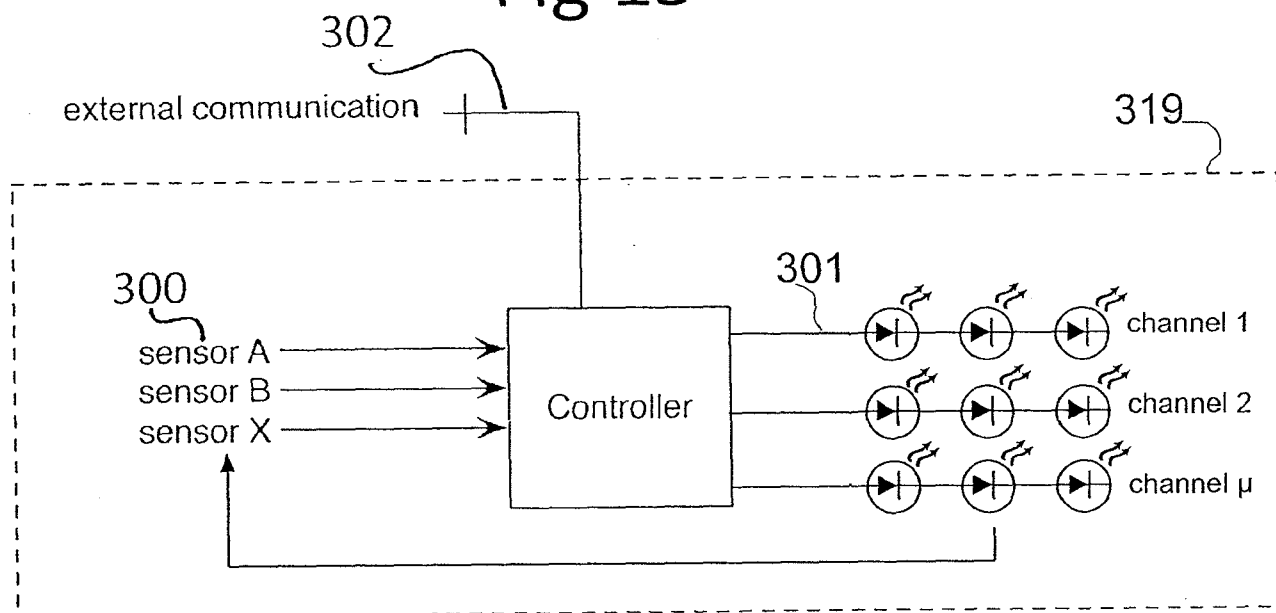


Fig 16

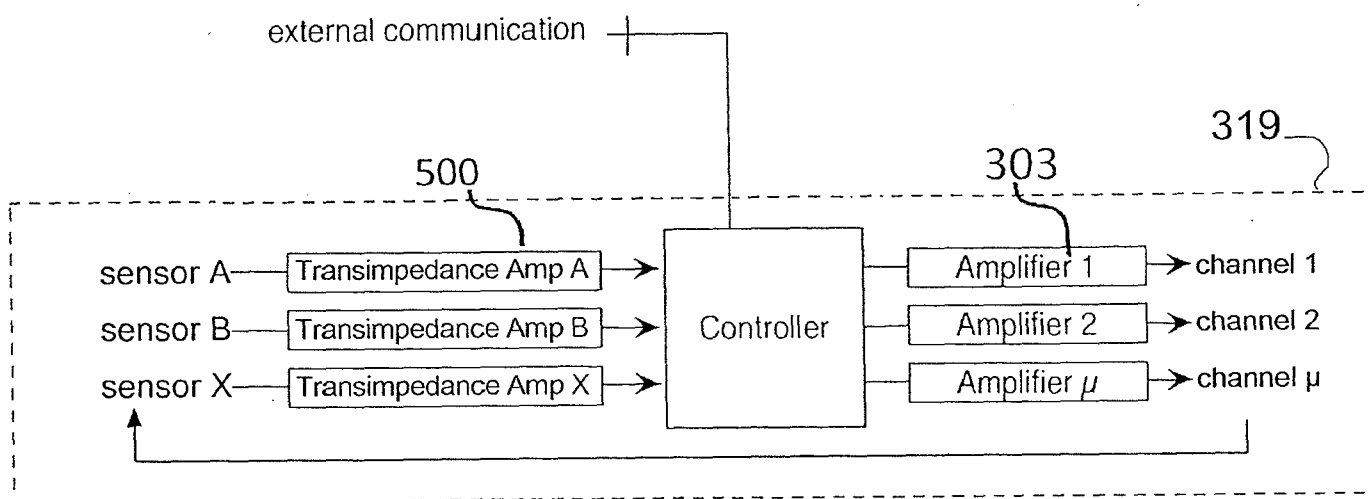


Fig 17

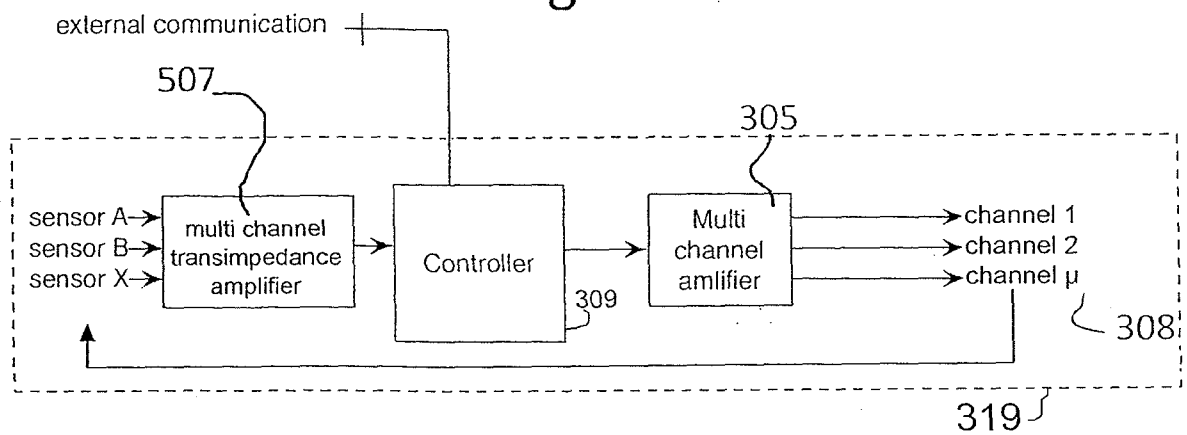
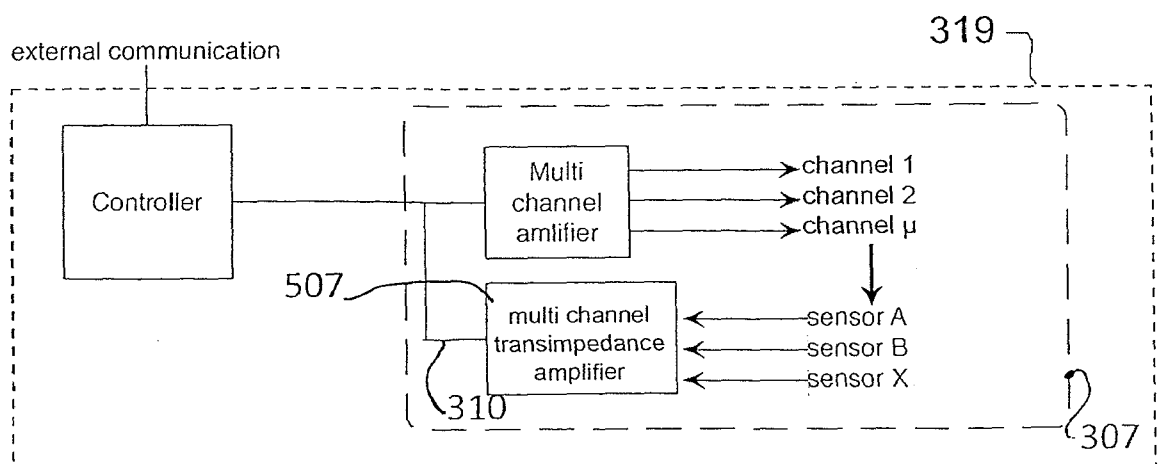
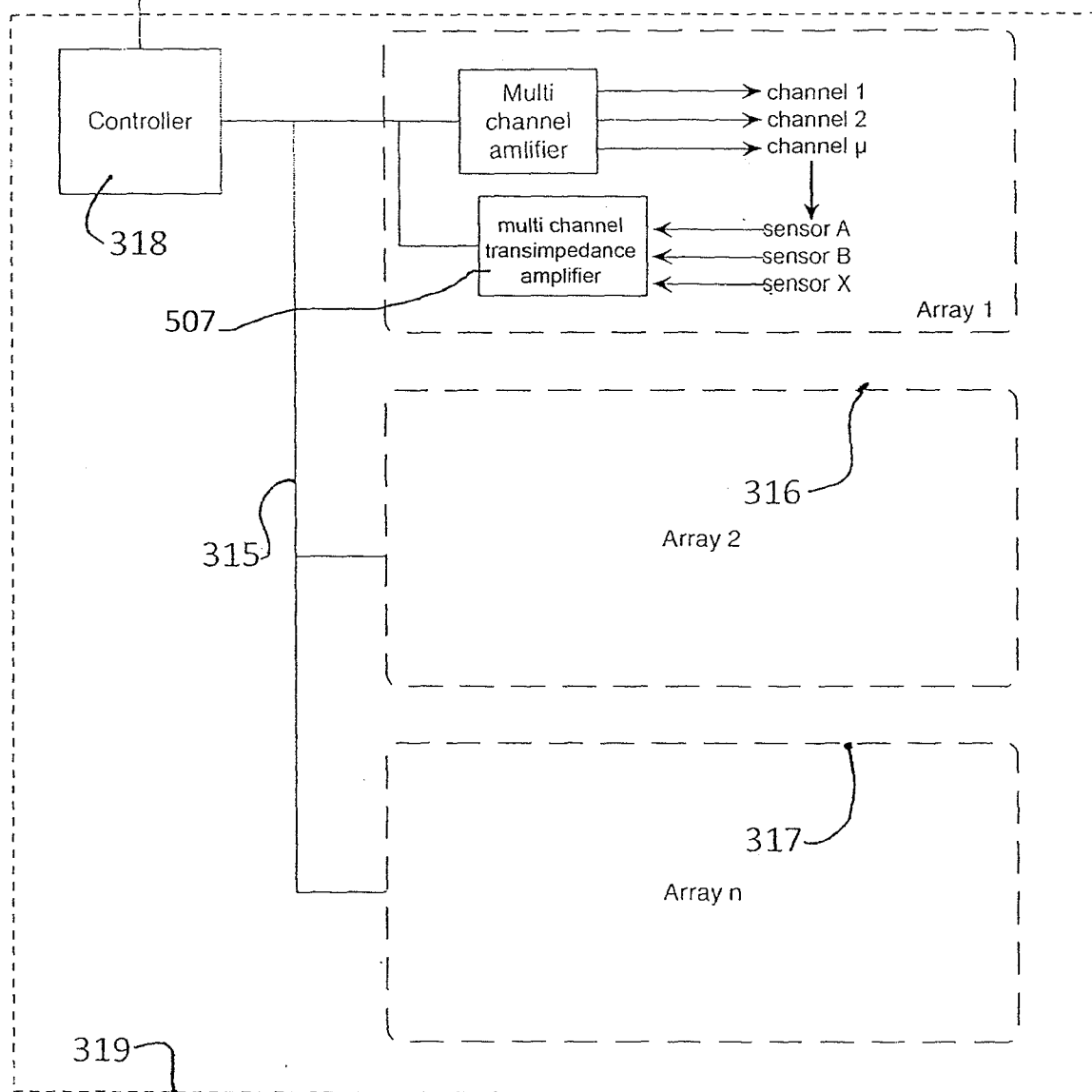


Fig 18



16/30  
Fig 19

external communication



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Fig 20

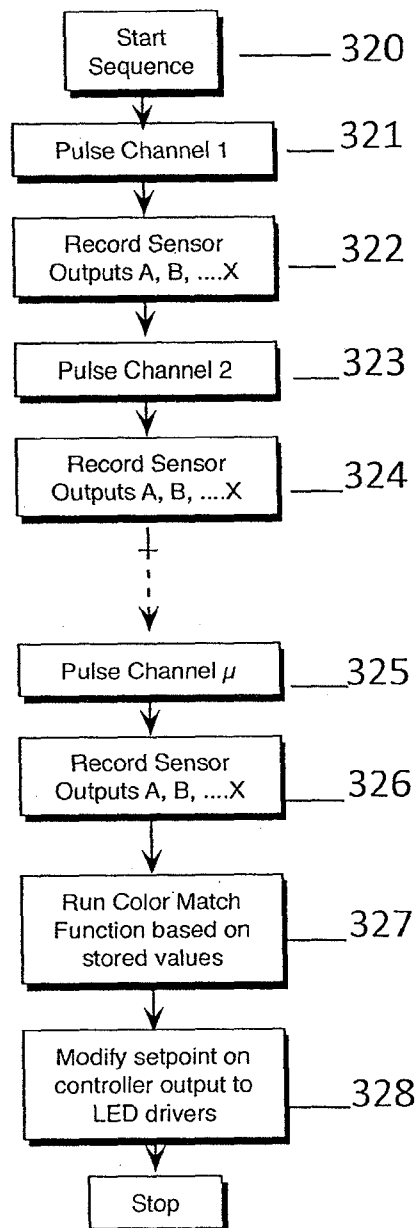


Fig 21

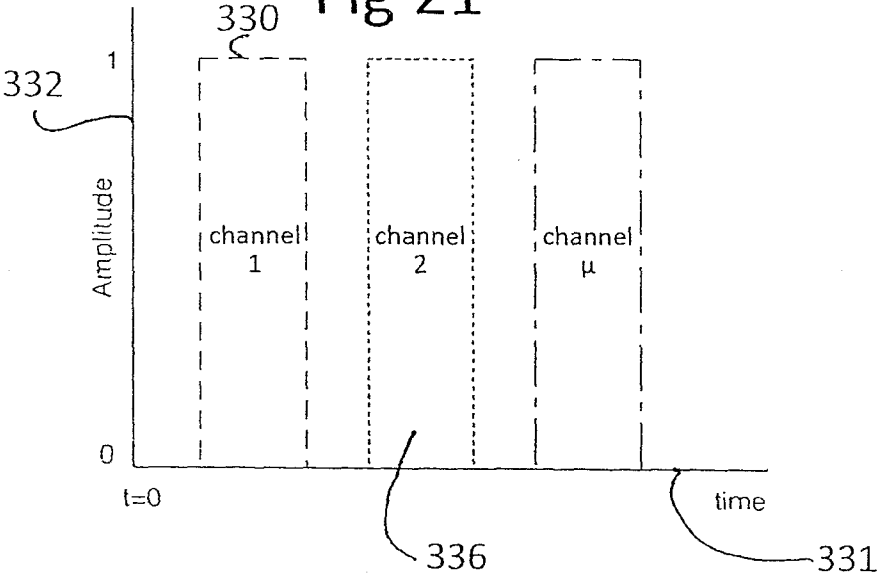


Fig 22

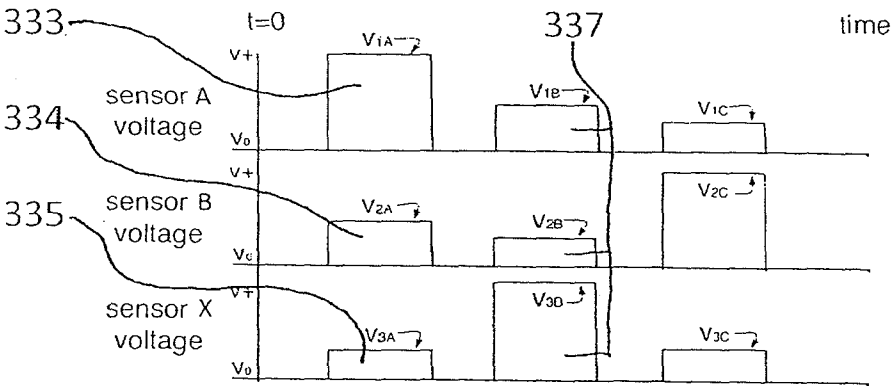


Fig 23

	341	342	343	344	345
	Channel	Channel	Channel	Condition	Condition
	1	2	$\mu$	$\beta$	$\Omega$
347 sensor A	$V_{A1}$	$V_{A2}$	$V_{A\mu}$	$V_{A\beta}$	$V_{A\Omega}$
sensor B	$V_{B1}$	$V_{B2}$	$V_{B\mu}$	$V_{B\beta}$	$V_{B\Omega}$
340 sensor X	$V_{X1}$	$V_{X2}$	$V_{X\mu}$	$V_{X\beta}$	$V_{X\Omega}$

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Fig 24

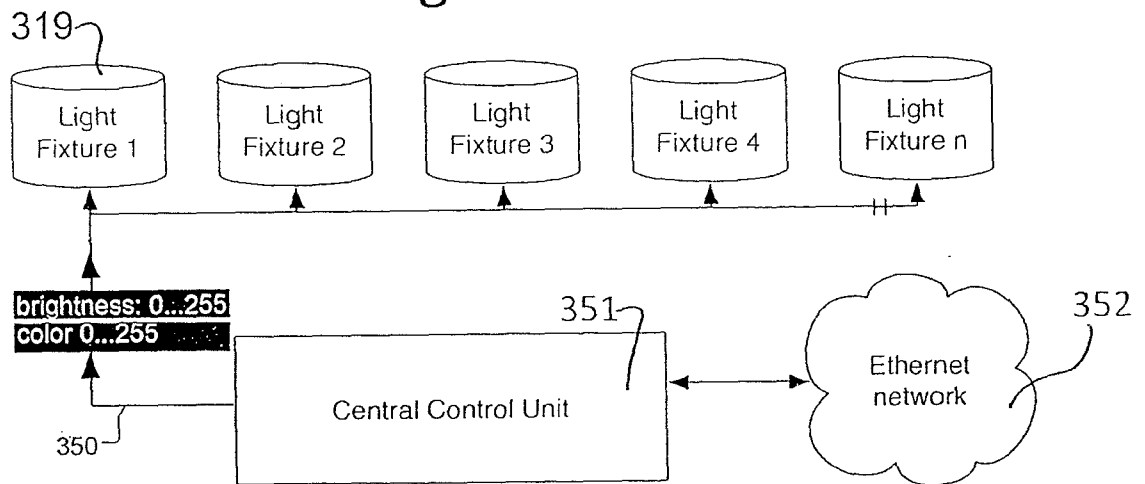


Fig 25

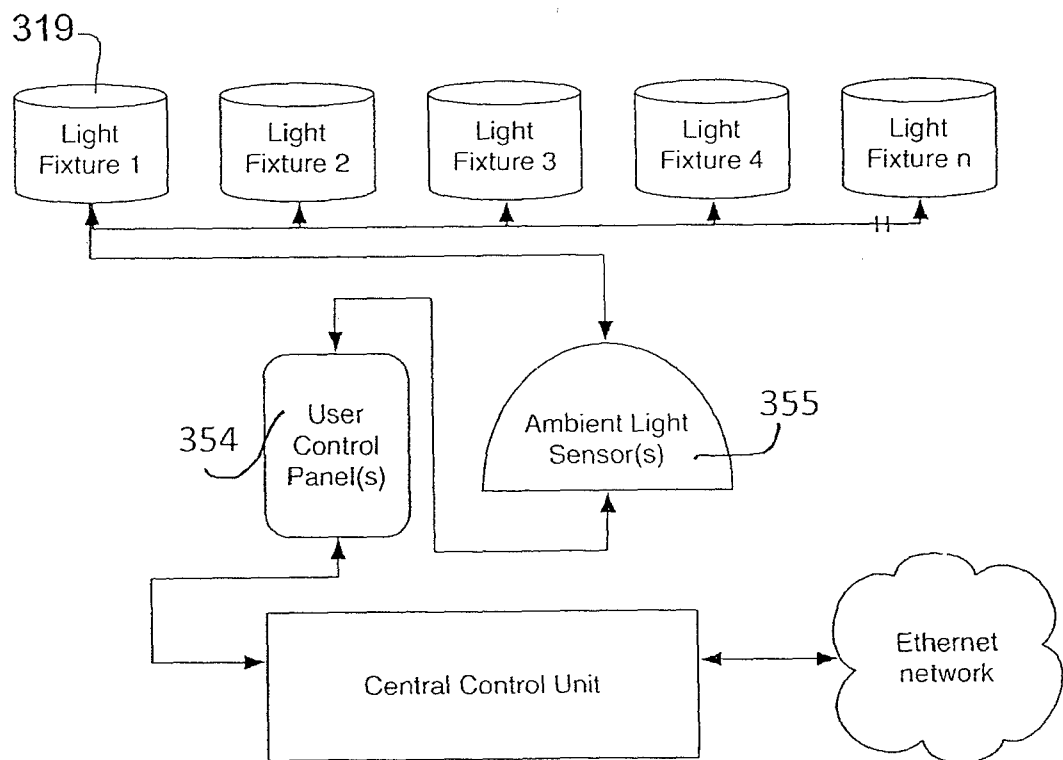
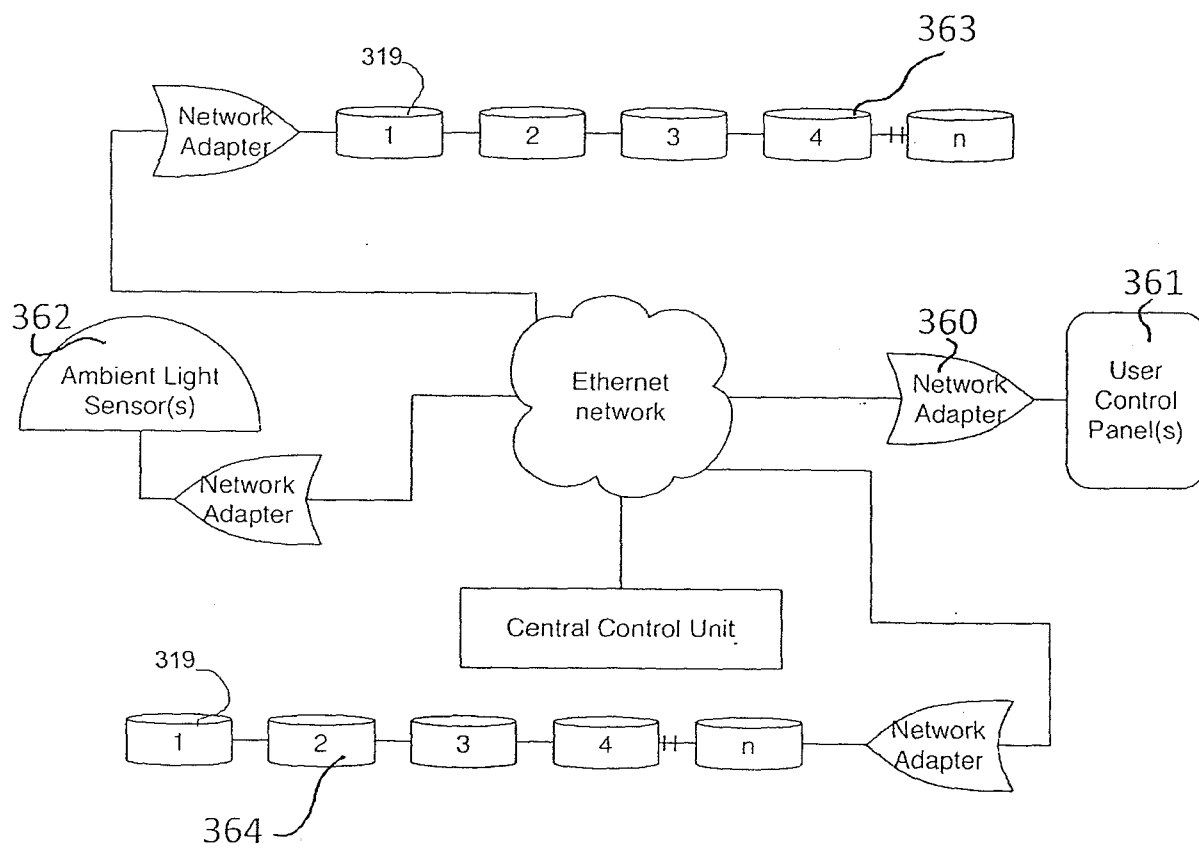


Fig 26





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Fig 27

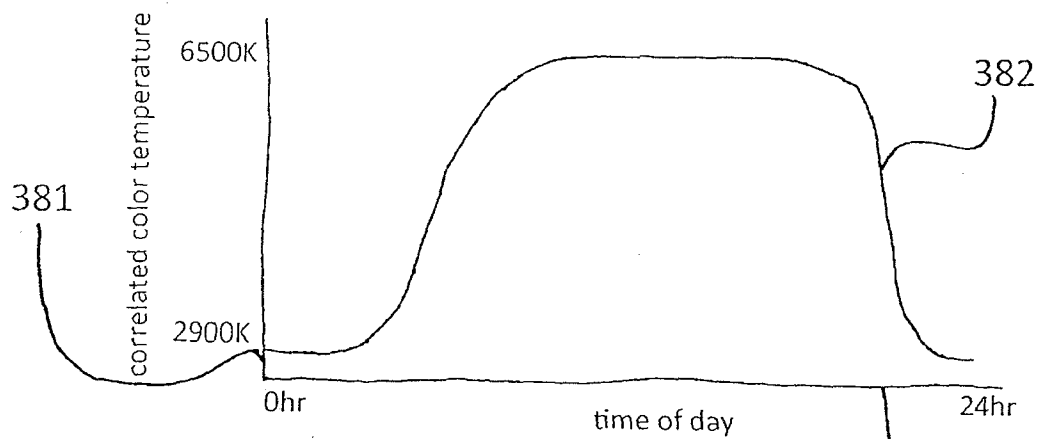
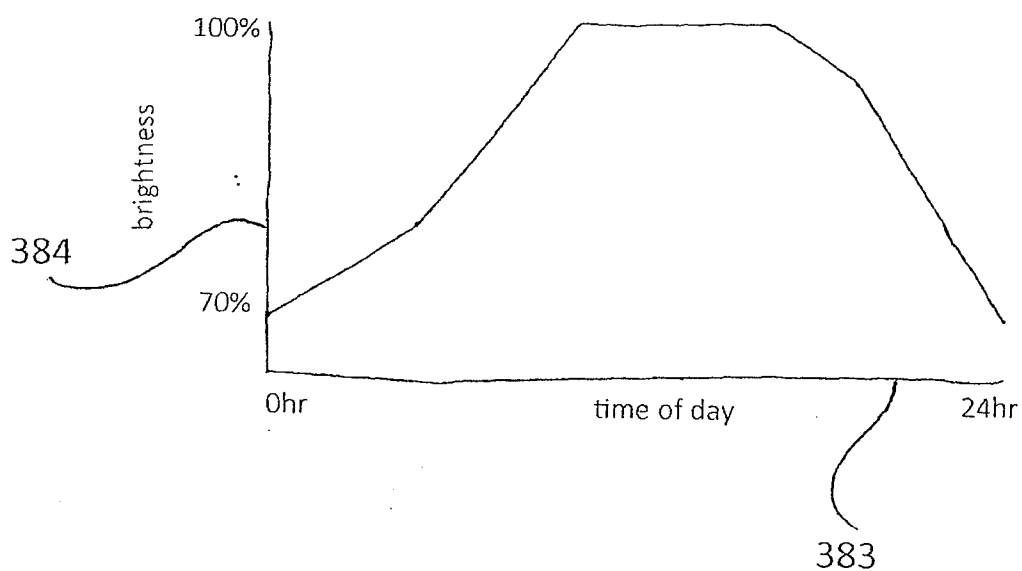
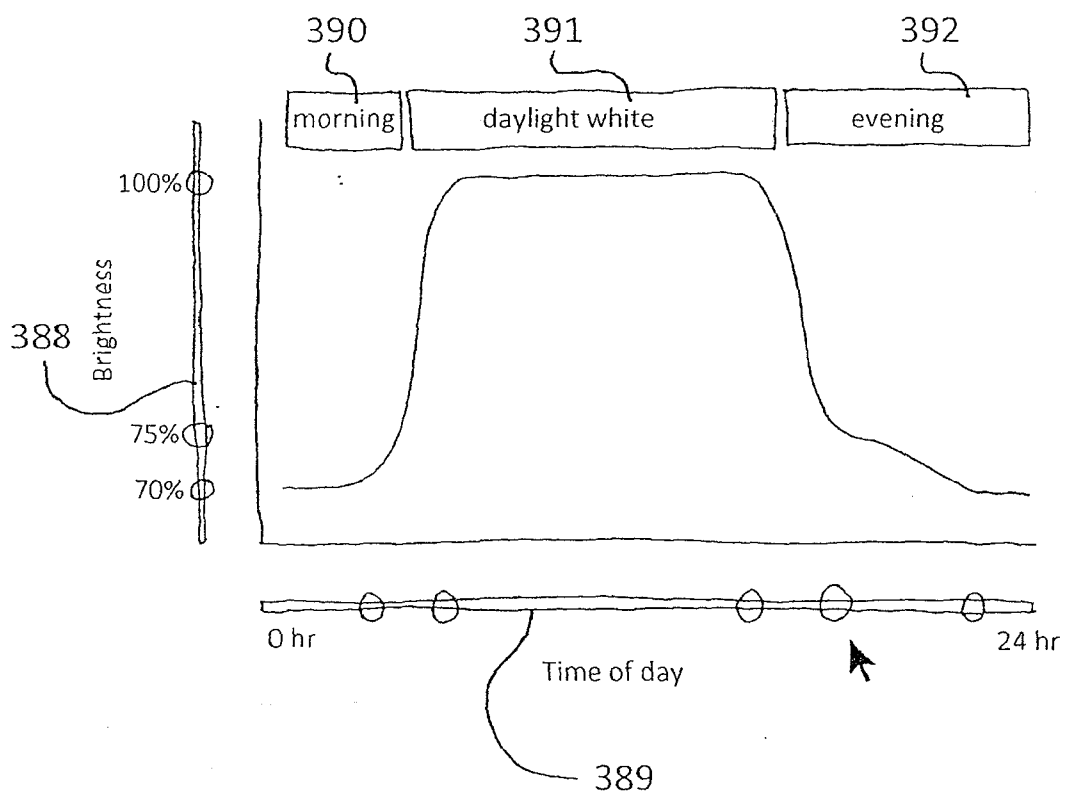


Fig 28



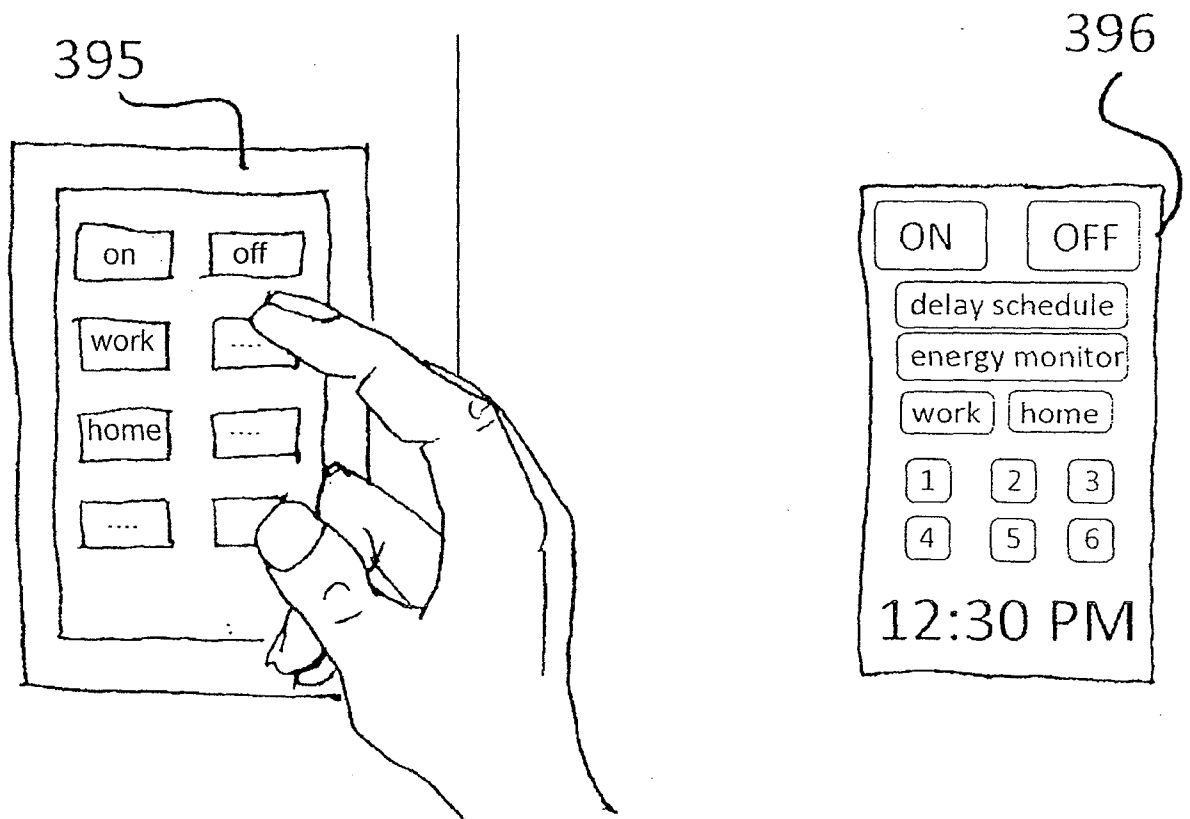
22/30

Fig 29



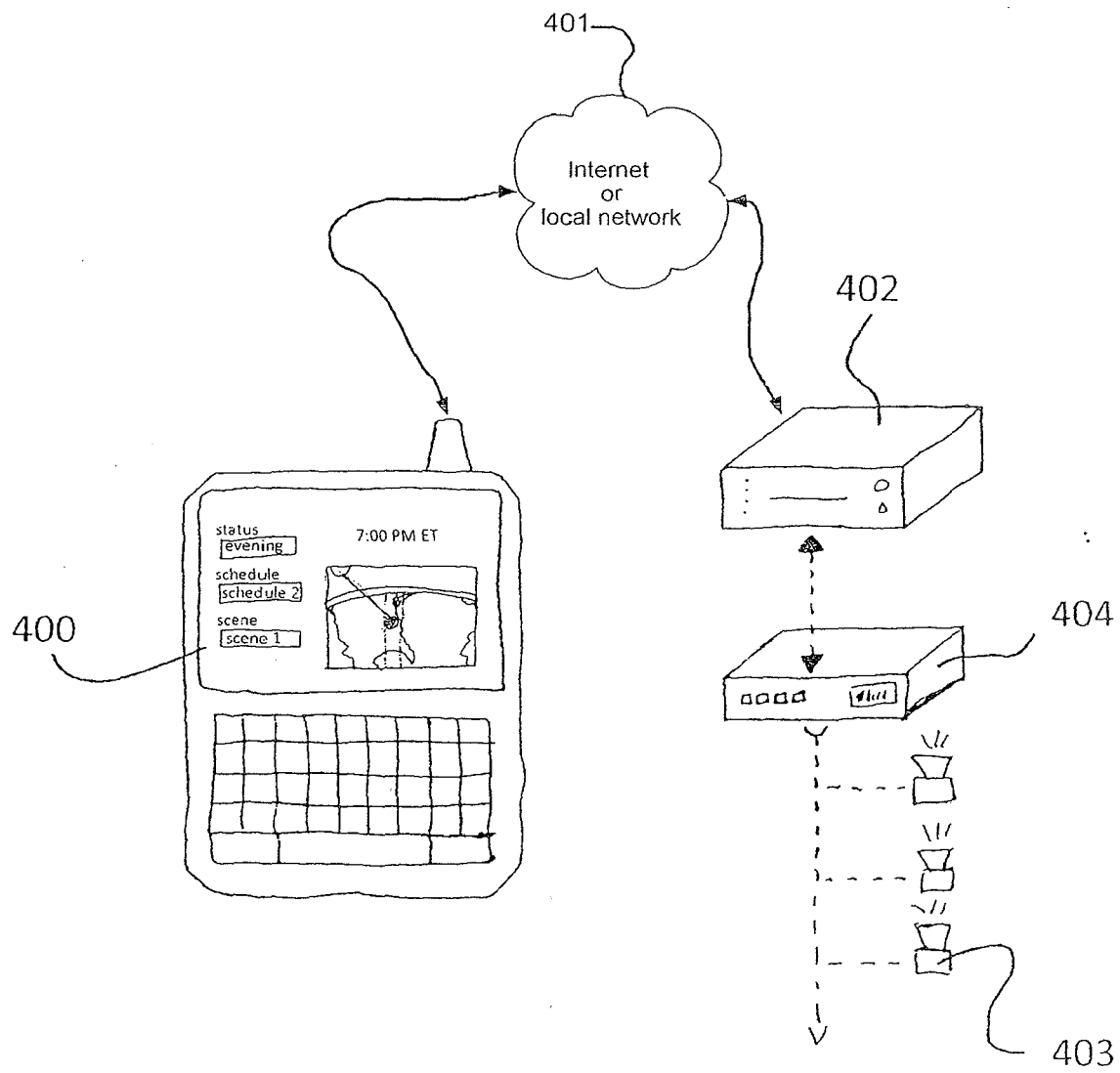
23/30

Fig 30



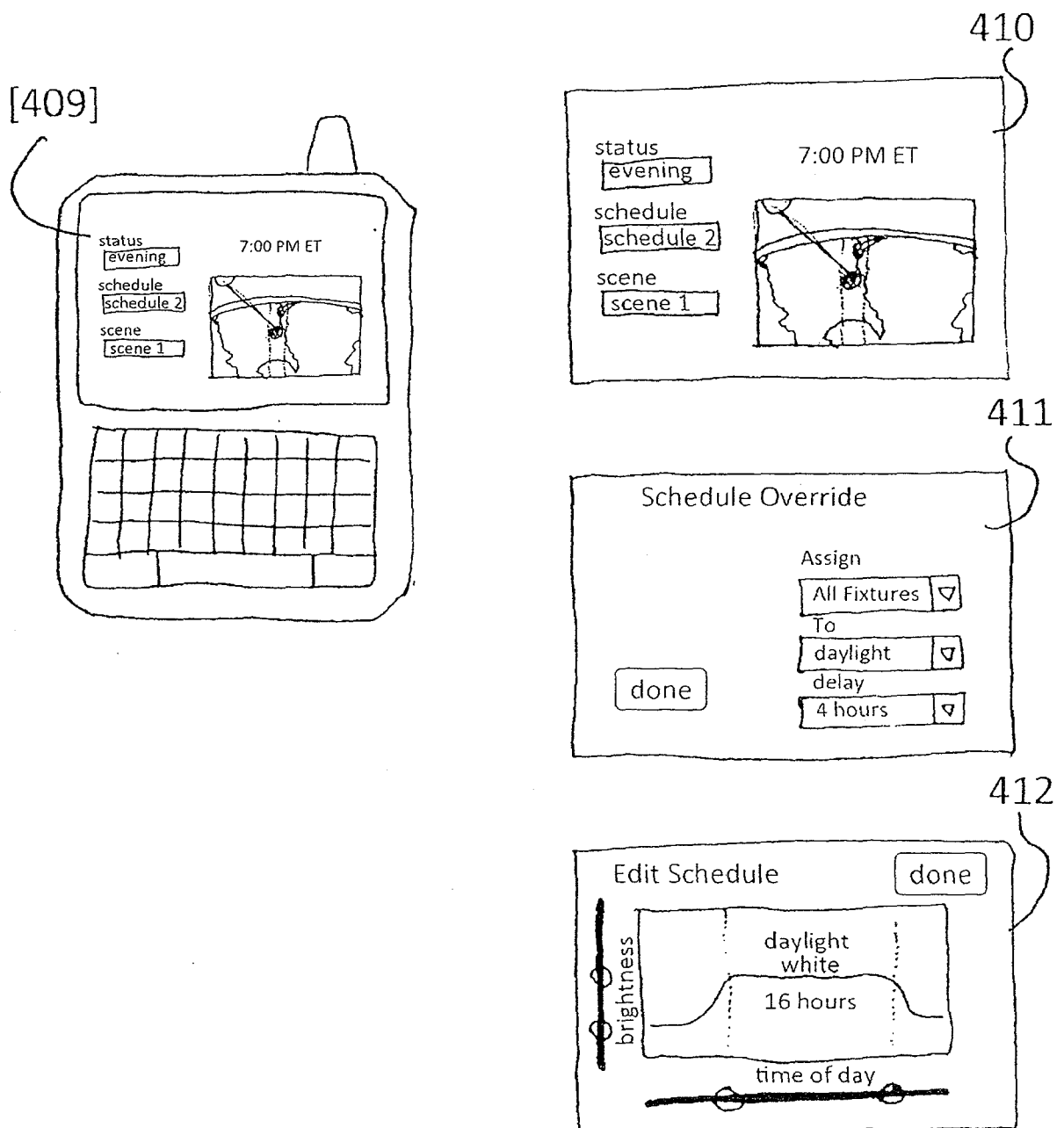
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Fig 31



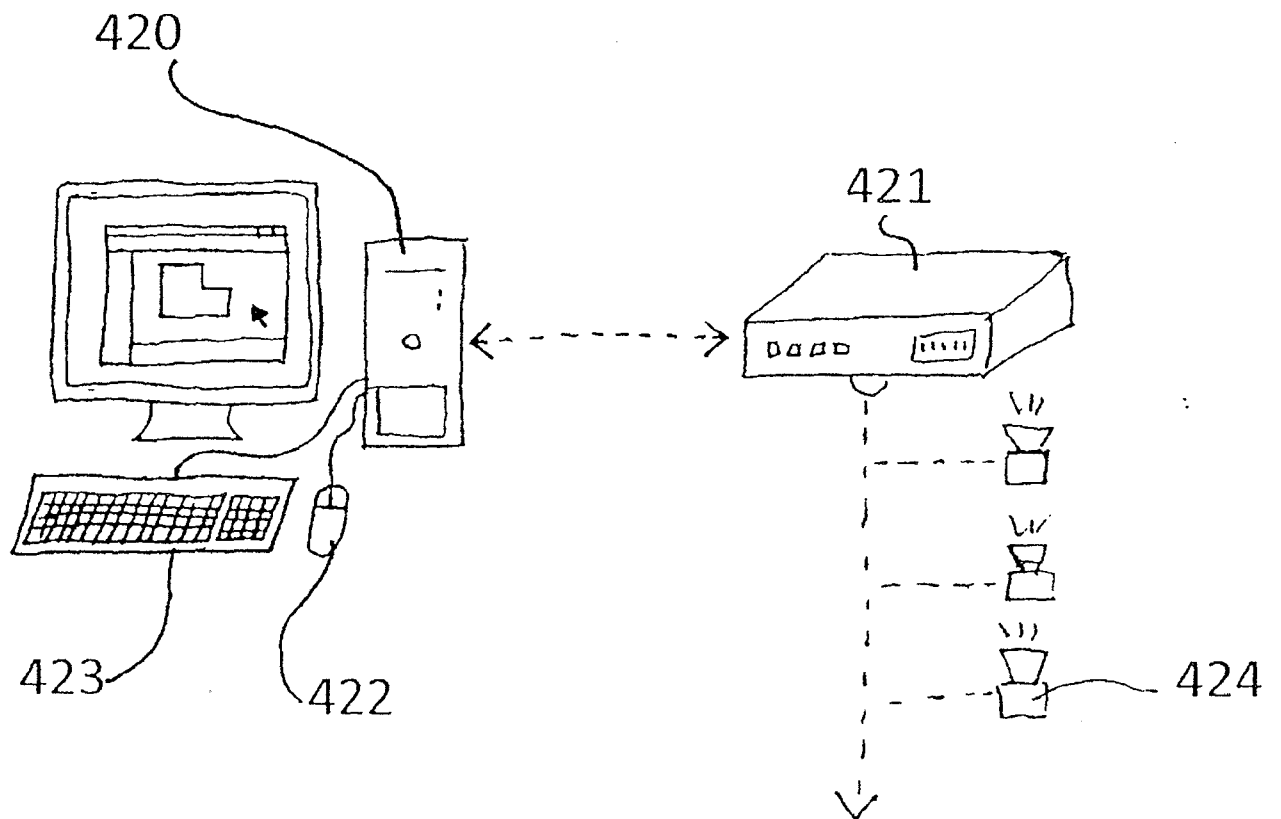
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Fig 32

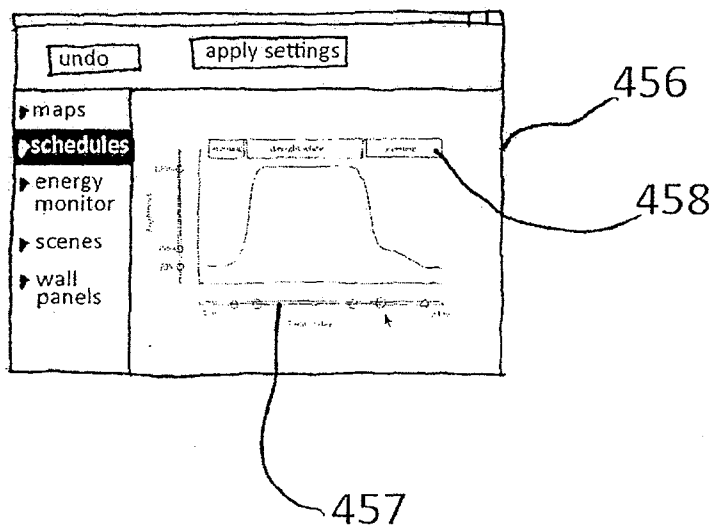
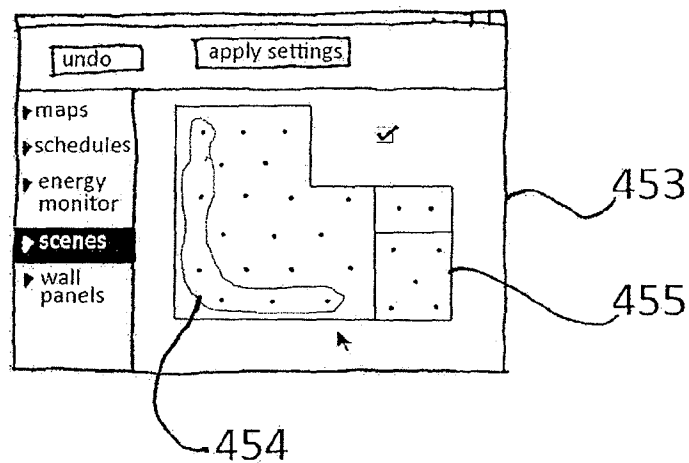
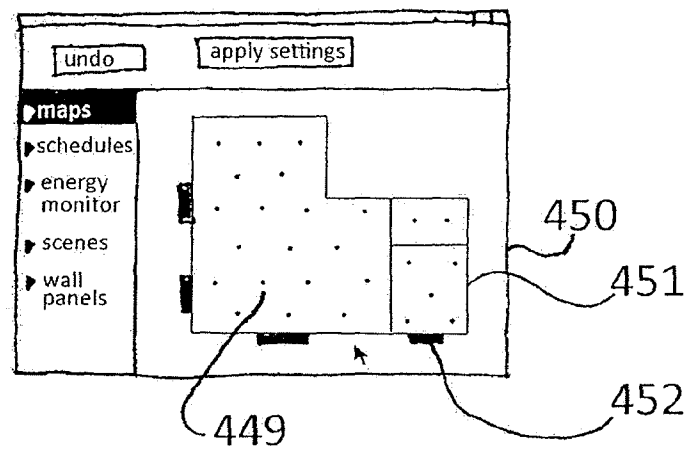


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Fig 33



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Fig 34



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Fig 35

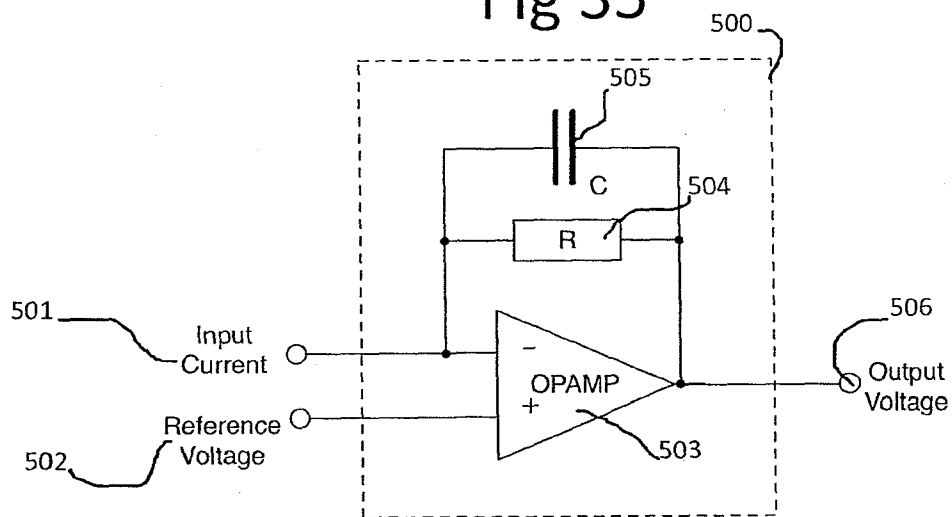
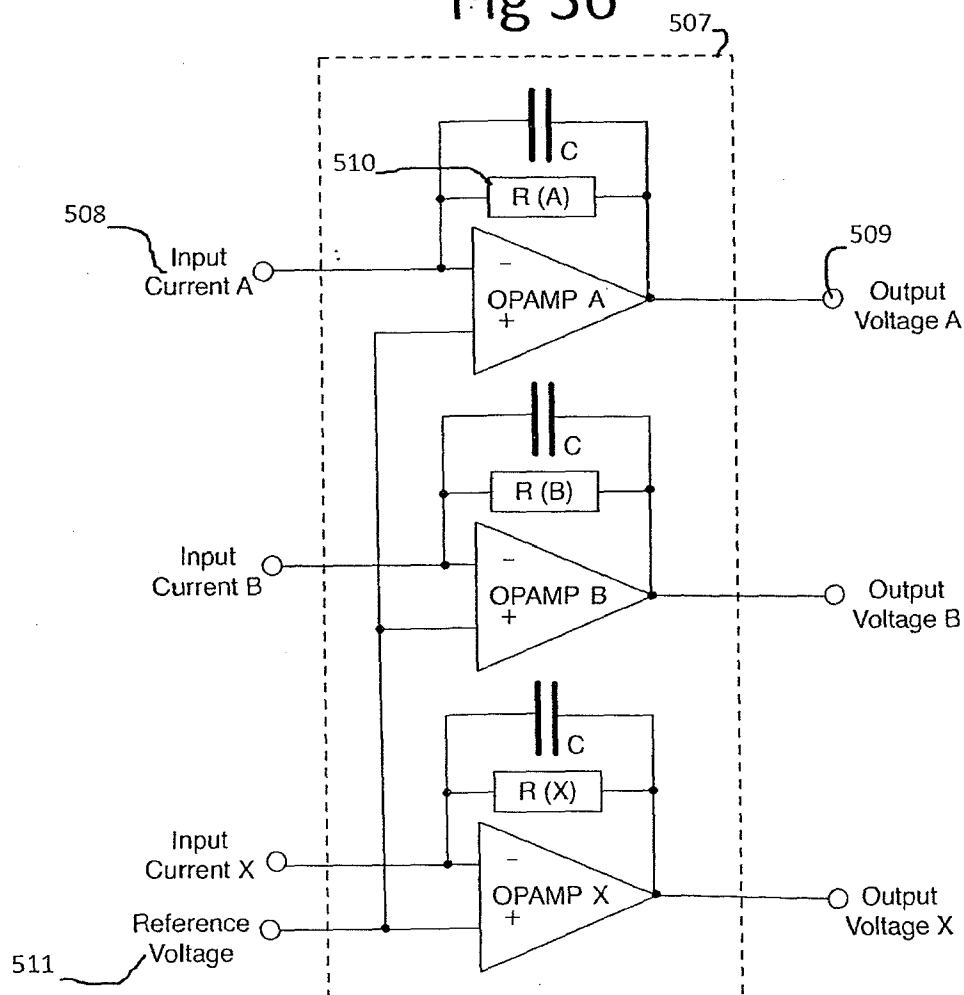


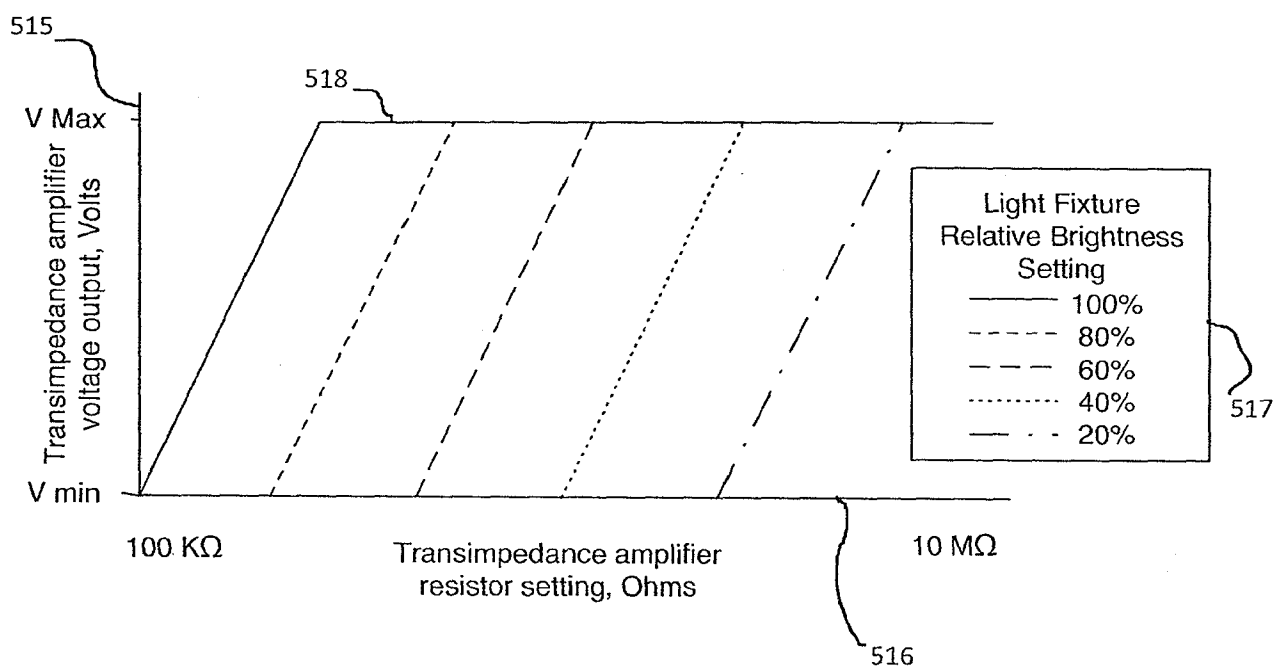
Fig 36





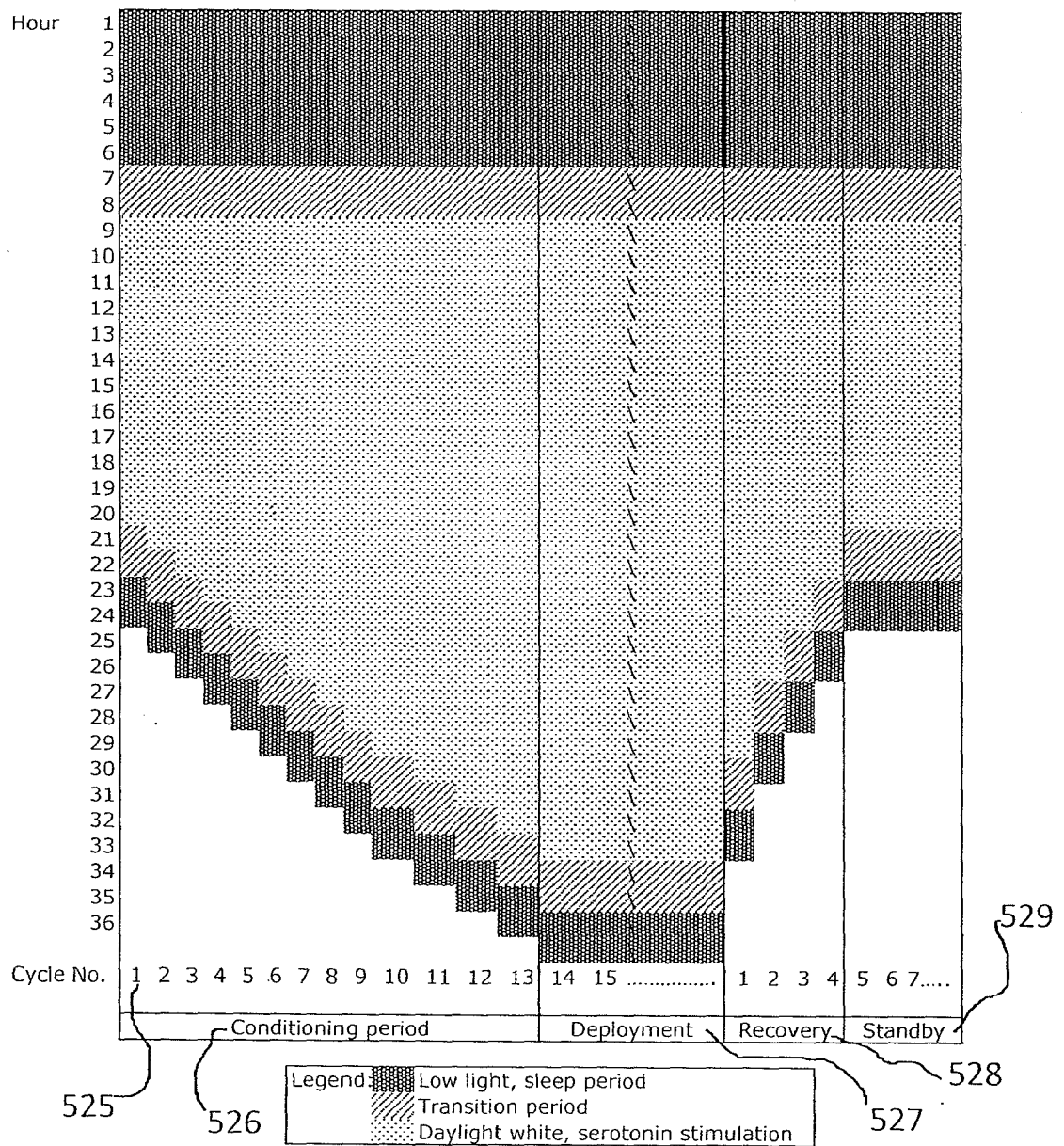
29/30

Fig 37



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Fig 38



## INTERNATIONAL SEARCH REPORT

International application No

PCT/US2010/051791

A. CLASSIFICATION OF SUBJECT MATTER  
 INV. H05B33/08  
 ADD.

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

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
 H05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7 573 210 B2 (ASHDOWN IAN [CA] ET AL) 11 August 2009 (2009-08-11) columns 7-12; figure 1 -----	1-43
X	WO 2009/044330 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]; PHILIPS INTELLECTUAL PROPERTY [DE] 9 April 2009 (2009-04-09) pages 4, 10-14; figures 1-3 -----	1-43
X	US 2009/128044 A1 (NEVINS MICHAEL OLEN [US]) 21 May 2009 (2009-05-21) pages 1-4; figures 1,2 -----	1-43



Further documents are listed in the continuation of Box C.



See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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Date of the actual completion of the international search

31 January 2011

Date of mailing of the international search report

04/02/2011

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2  
 NL - 2280 HV Rijswijk  
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 Fax: (+31-70) 340-3016

Authorized officer

Morrish, Ian

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2010/051791

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 7573210	B2	11-08-2009	CA 2583355 A1 20-04-2006
			WO 2006039789 A1 20-04-2006
			CN 101124853 A 13-02-2008
			CN 101128979 A 20-02-2008
			EP 1803331 A1 04-07-2007
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			US 2007108846 A1 17-05-2007
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WO 2009044330	A1	09-04-2009	NONE
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US 2009128044	A1	21-05-2009	NONE
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