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(54) **LED LIGHTING THAT HAS CONTINUOUS AND ADJUSTABLE COLOR TEMPERATURE (CT), WHILE MAINTAINING A HIGH CRI**

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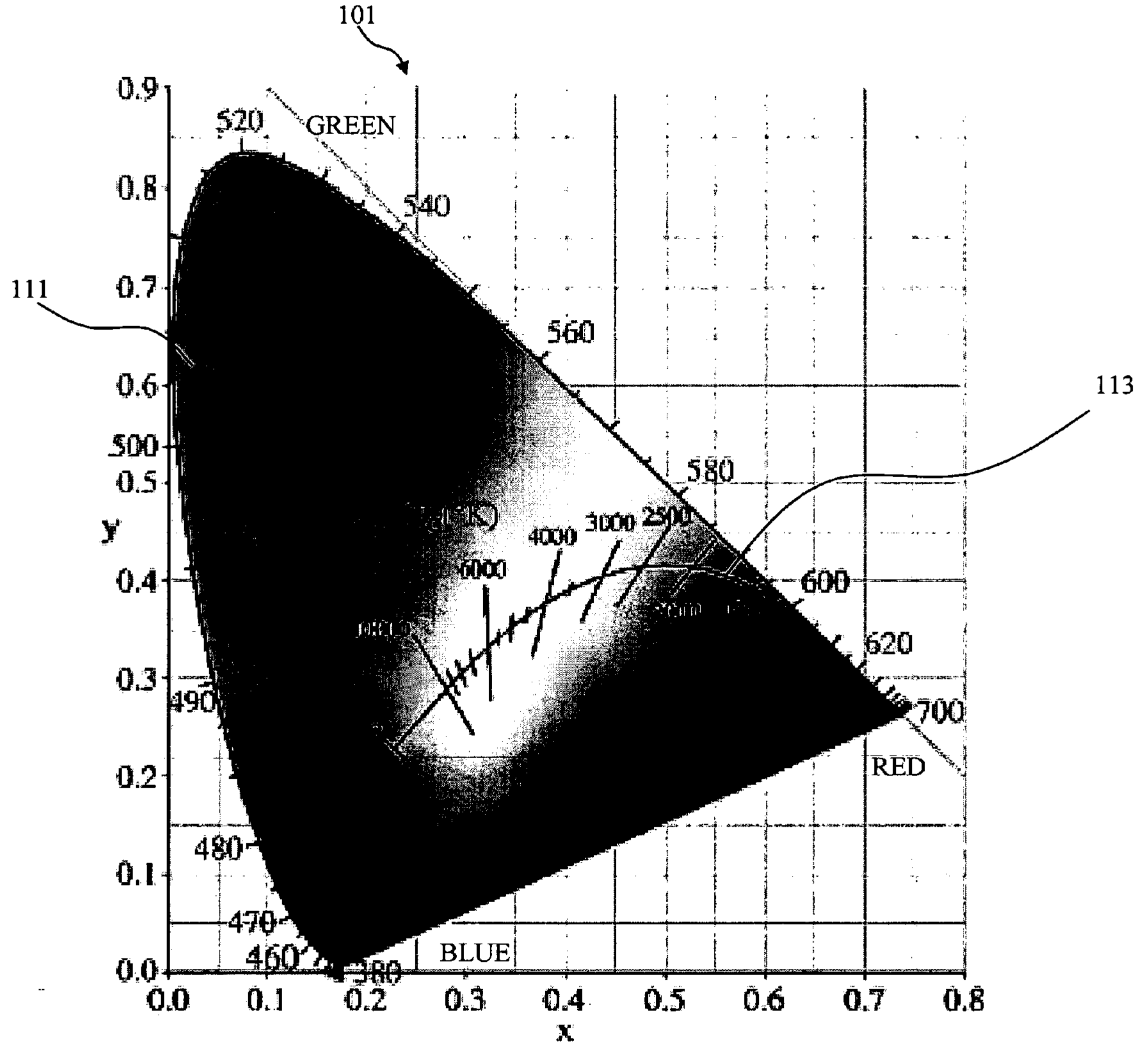
(57) **ABSTRACT**

A modular, standalone, and multi-functional electronic and mechanical platform for light-emitting diode (LED) lighting applications that has continuous and adjustable color temperature (CT) is provided. In particular, a modular LED device is utilized as a standalone lighting device or, alternatively, as a universal and generic building block for forming lighting devices for lighting application. The modular LED device includes an LED circuit, a digital signal processor (DSP), a network interface, and a power supply that can be packaged in a compact, thermally controlled housing. Additionally, the housing can provide alignment and fastening mechanisms for easily coupling one modular LED device to another modular LED device.



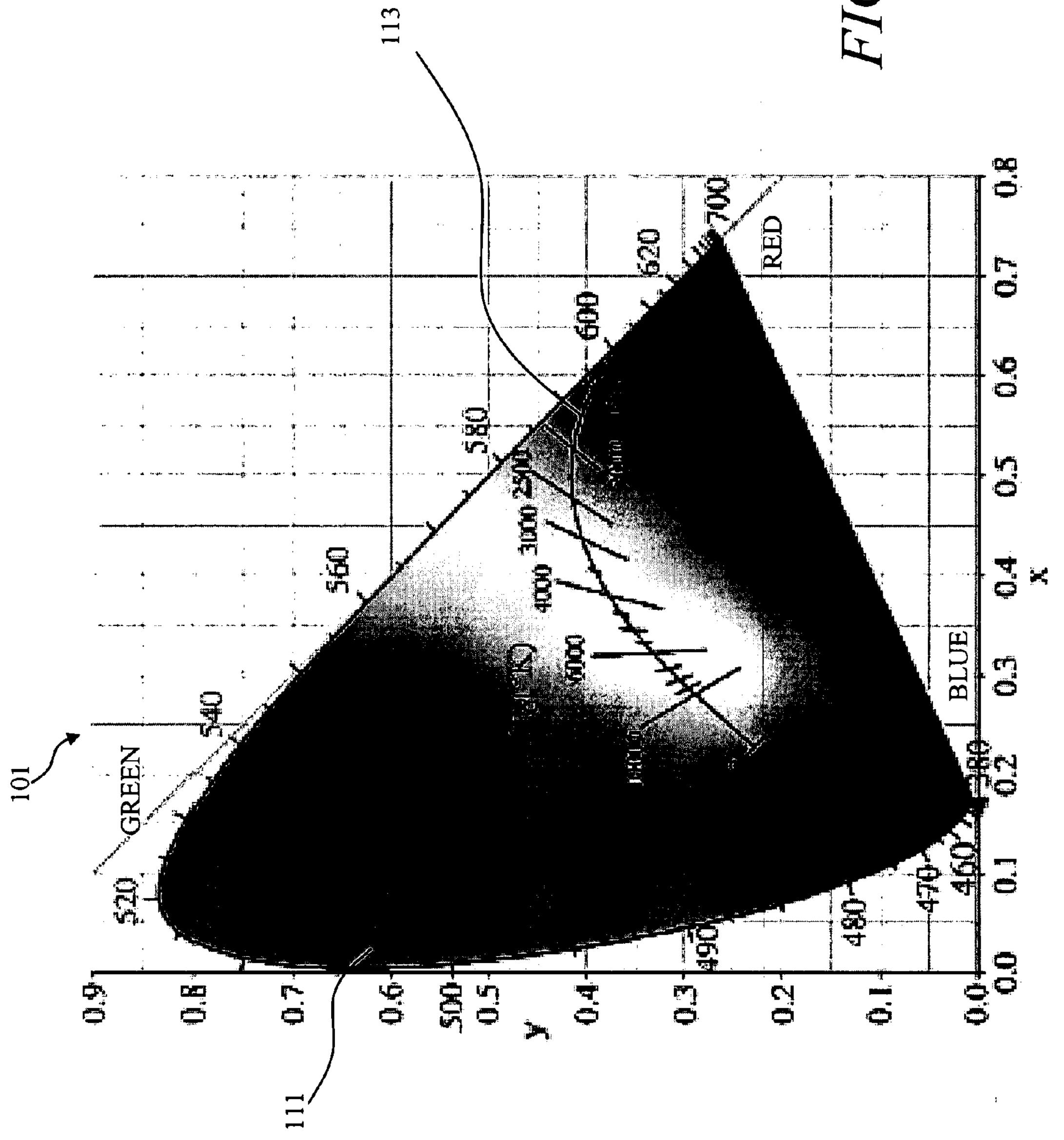

101
111
113
GREEN
RED
BLUE
520
540
560
580
600
620
700
500
490
480
470
460
380
2500
3000
4000
6000
10000
y
x
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

FIG. 1

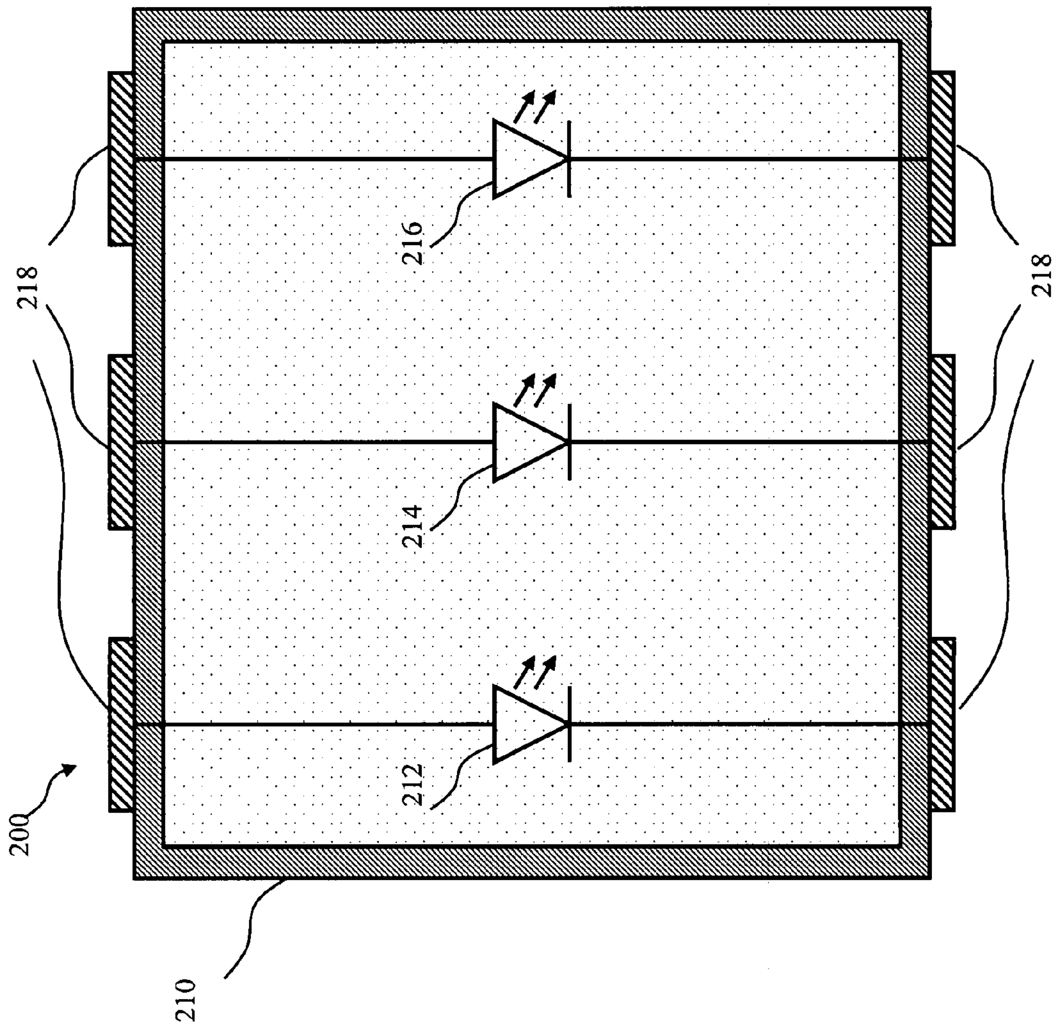


FIG. 2A

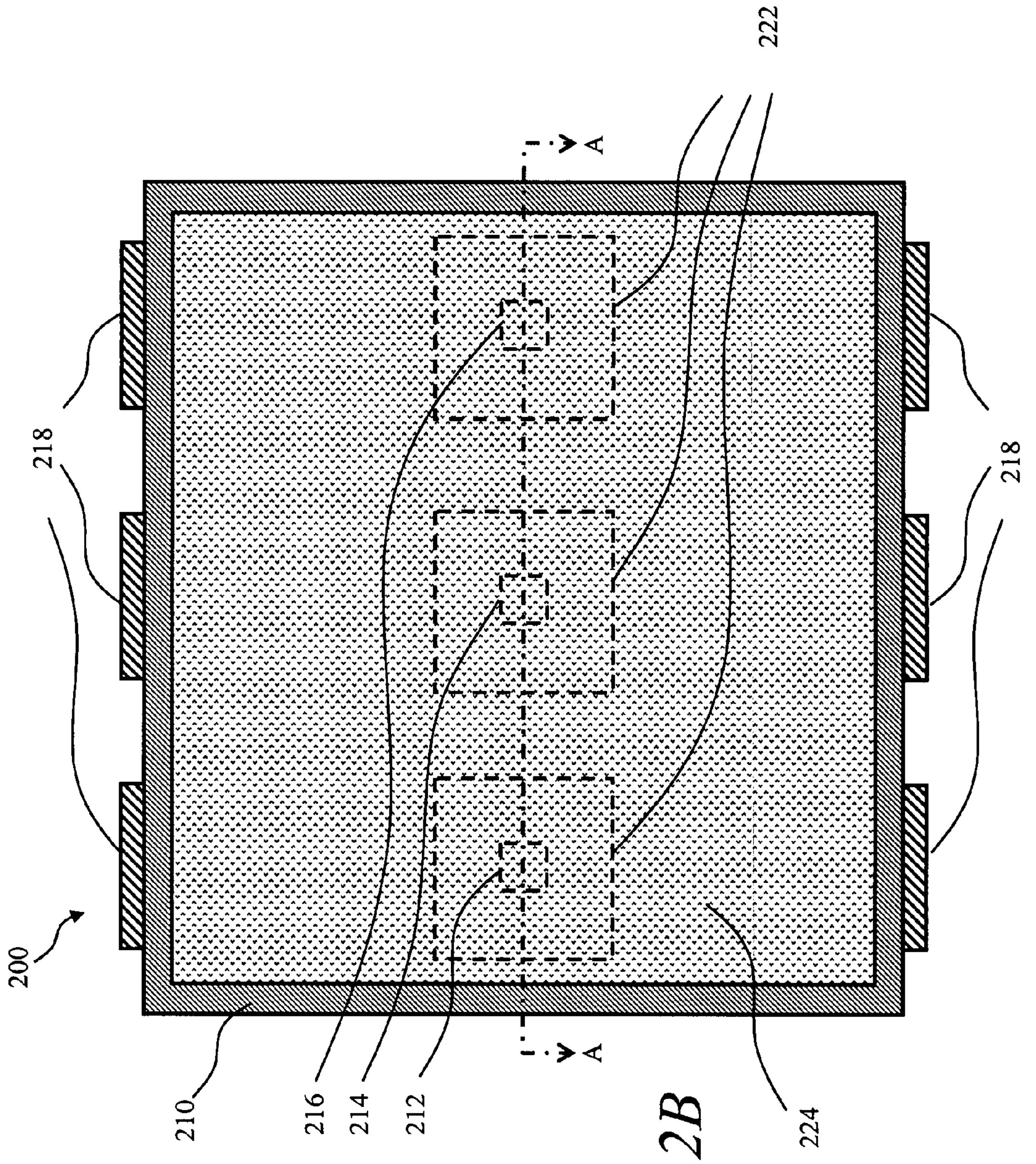


FIG. 2B

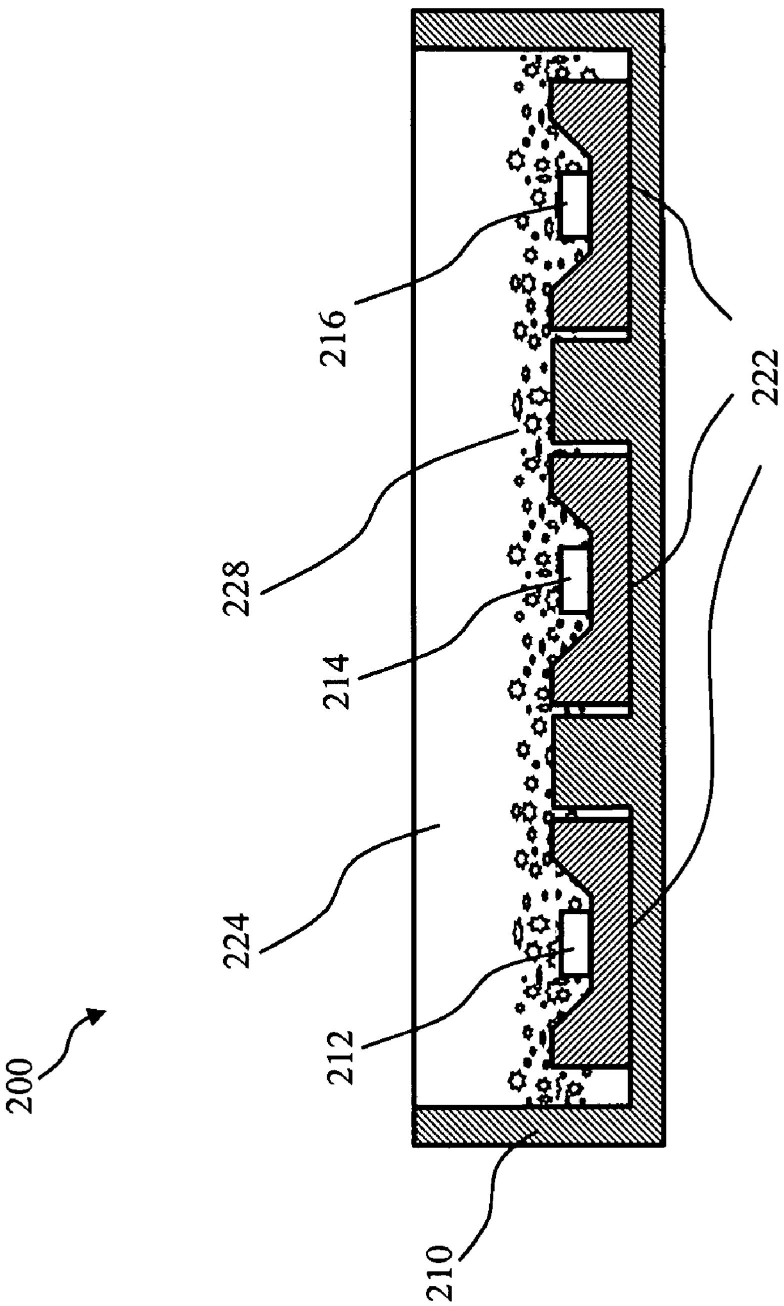


FIG. 2C

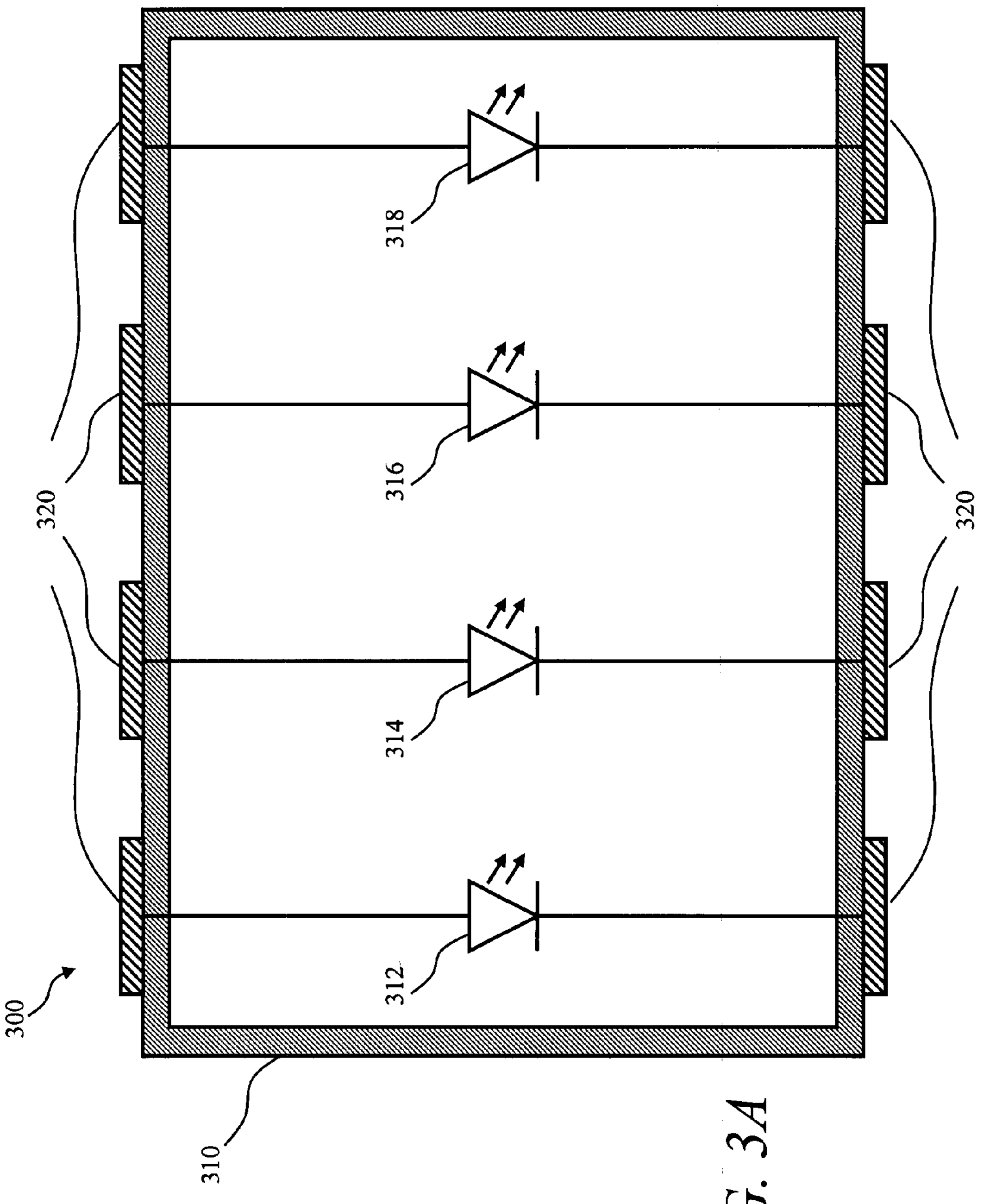


FIG. 3A

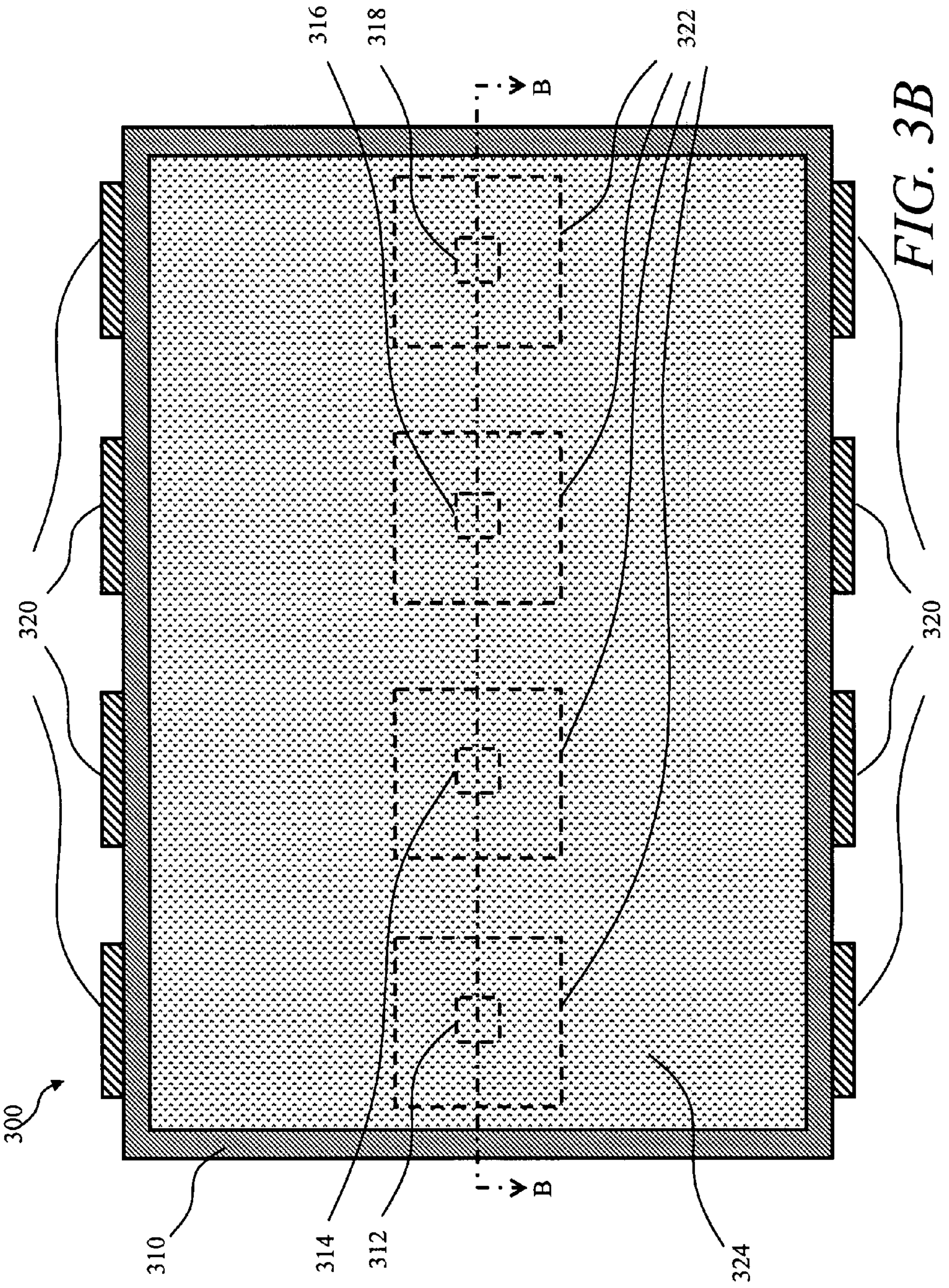


FIG. 3B

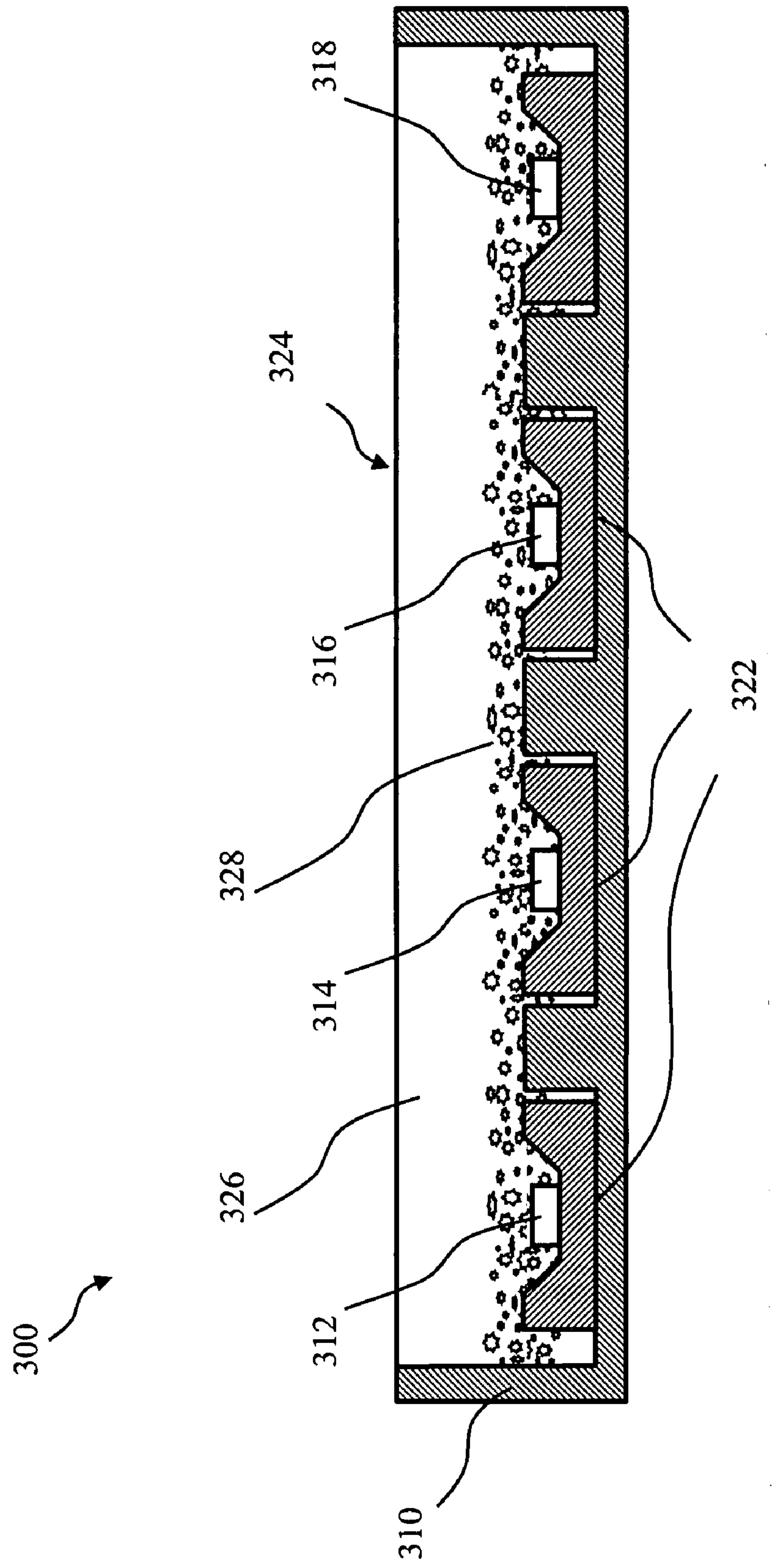


FIG. 3C

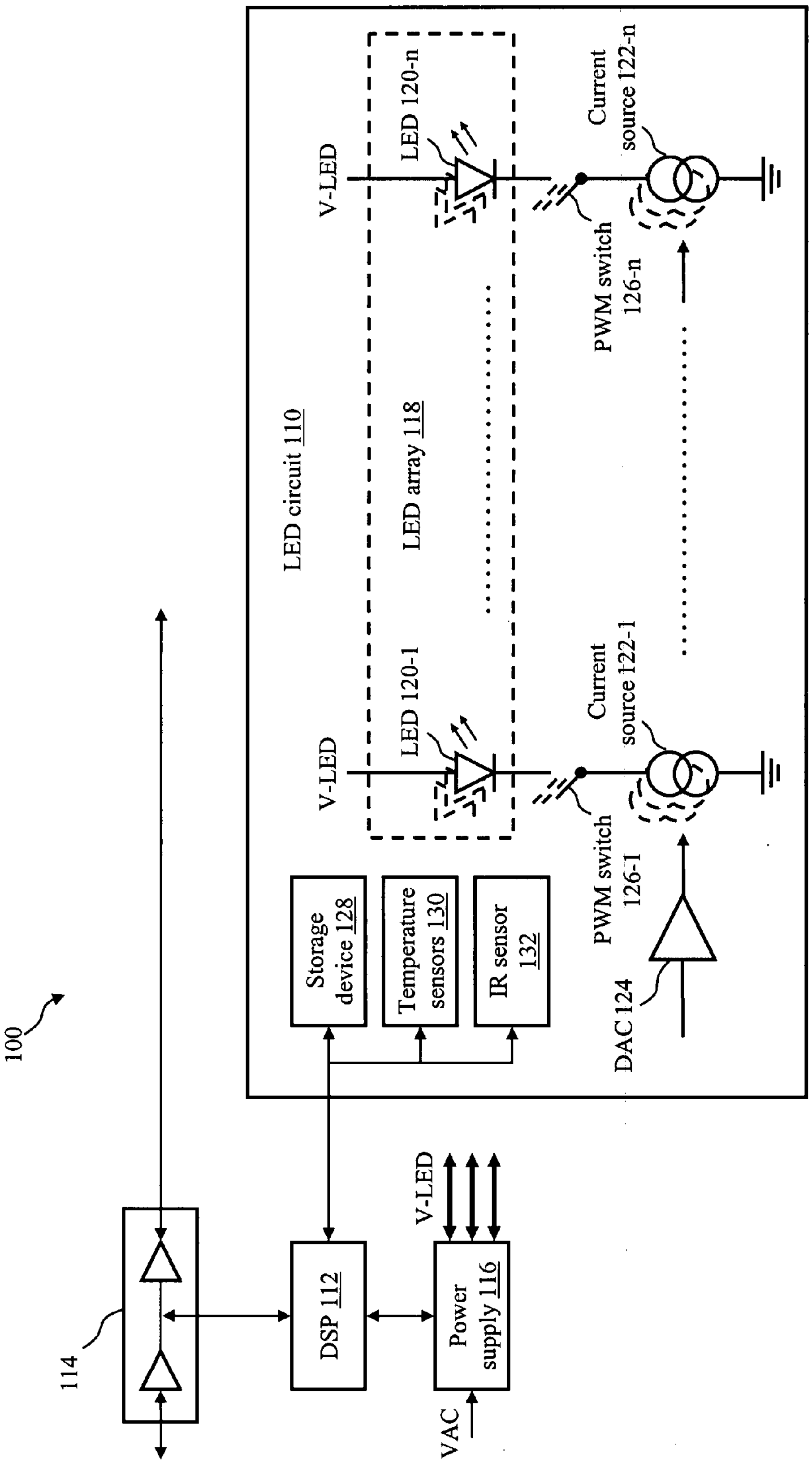

100
114
DSP 112
Power supply 116
VAC
V-LED
LED circuit 110
Storage device 128
Temperature sensors 130
IR sensor 132
DAC 124
PWM switch 126-1
Current source 122-1
LED 120-1
V-LED
LED array 118
V-LED
LED 120-n
PWM switch 126-n
Current source 122-n

FIG. 4

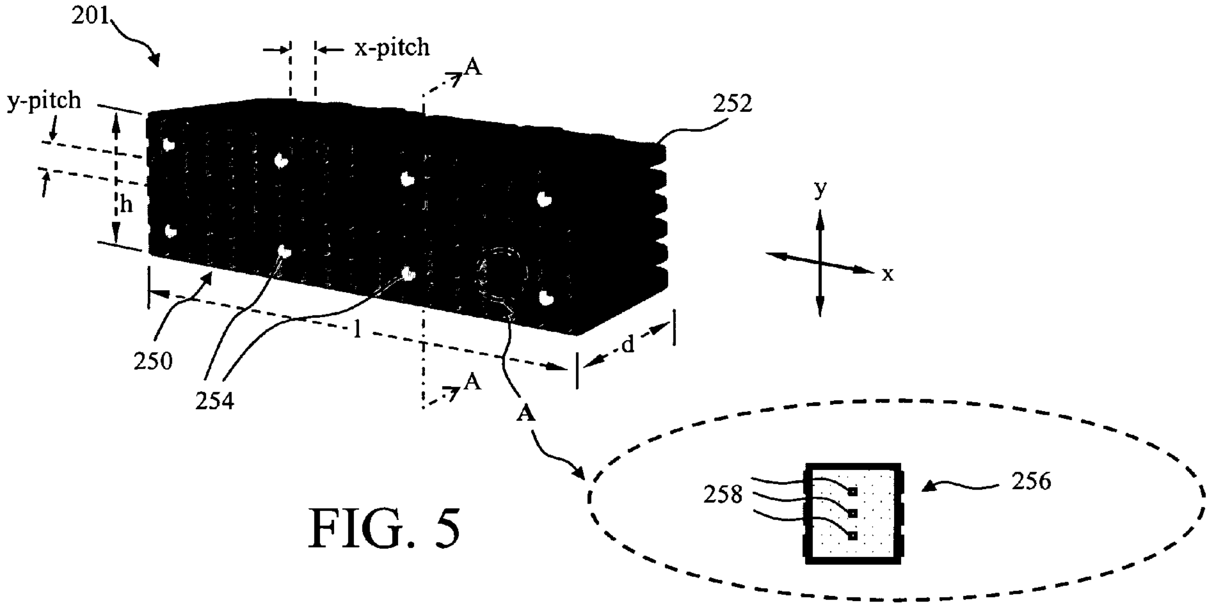

201
x-pitch
A
y-pitch
252
h
y
x
250
l
d
254
A
A
258
256

FIG. 5

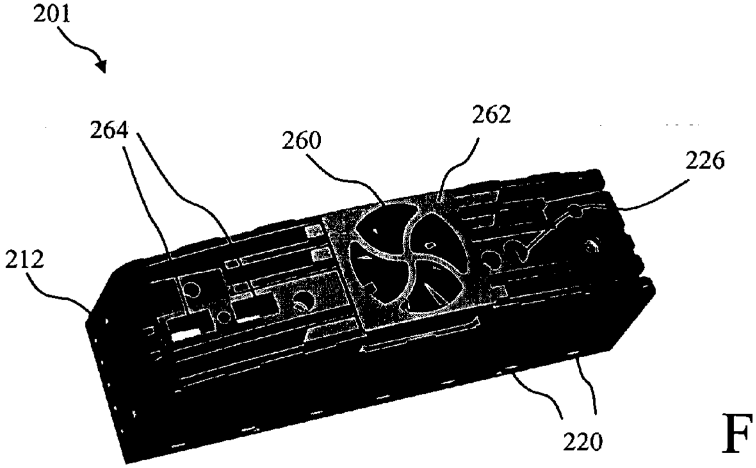

201
264
260
262
226
212
220

FIG. 6

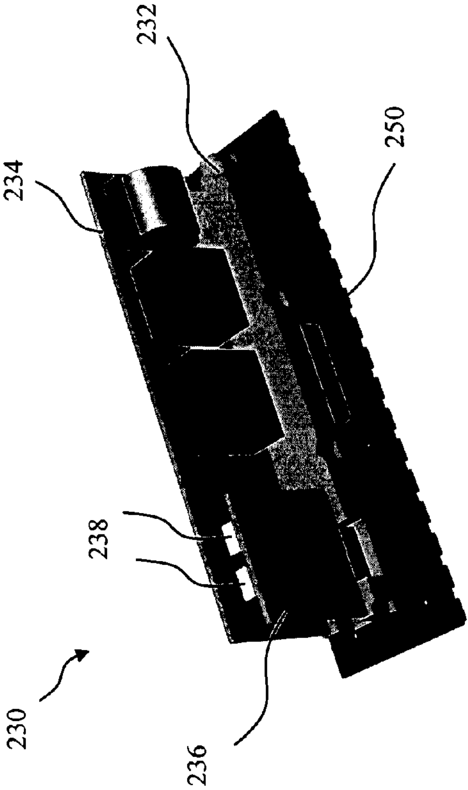


FIG. 7A

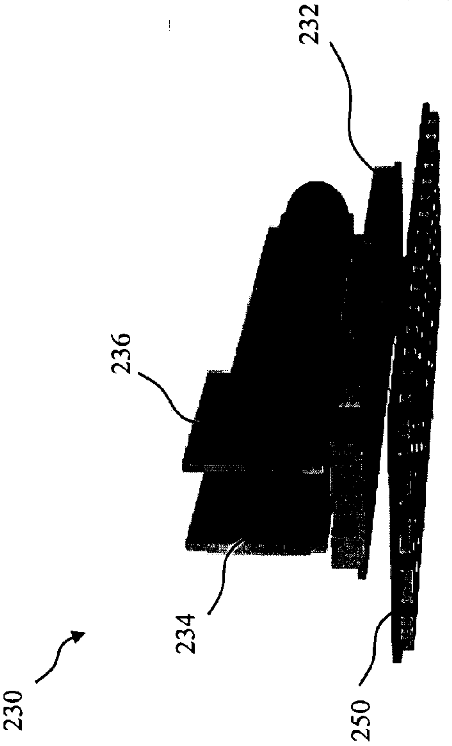


FIG. 7B

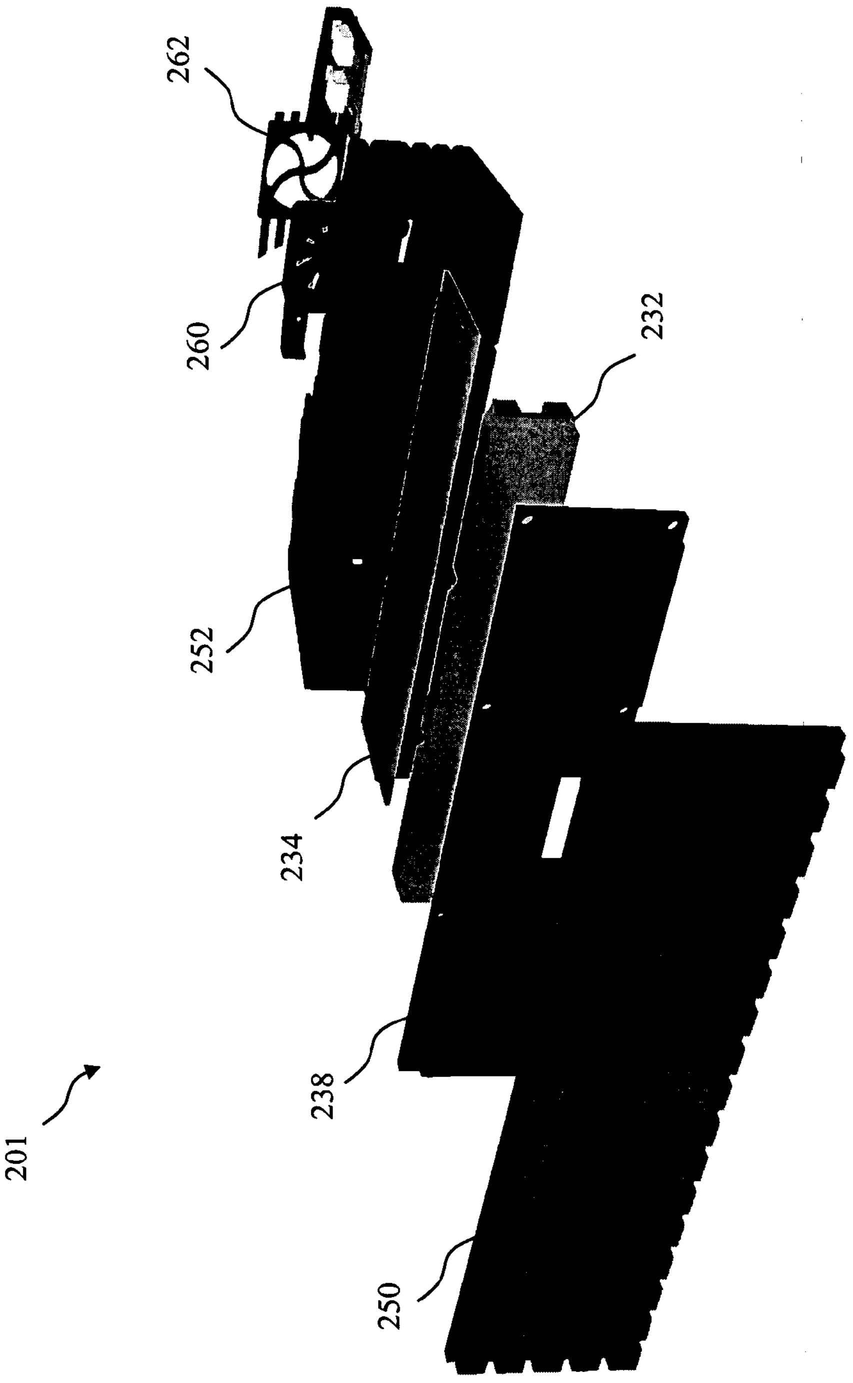


FIG. 8

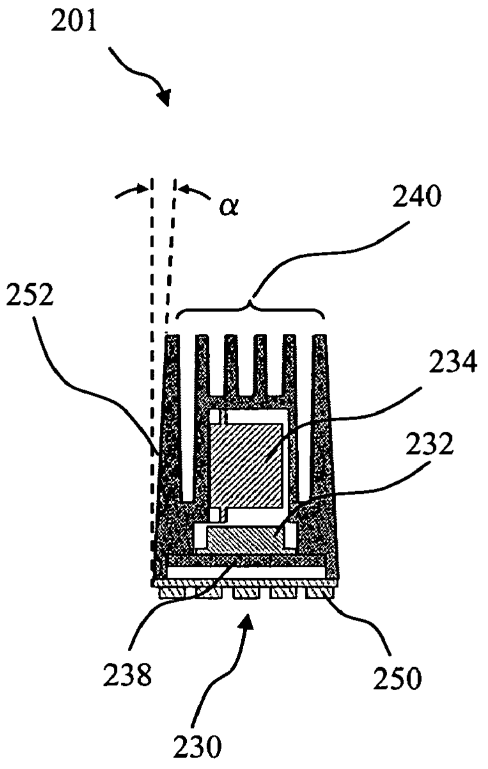


FIG. 9

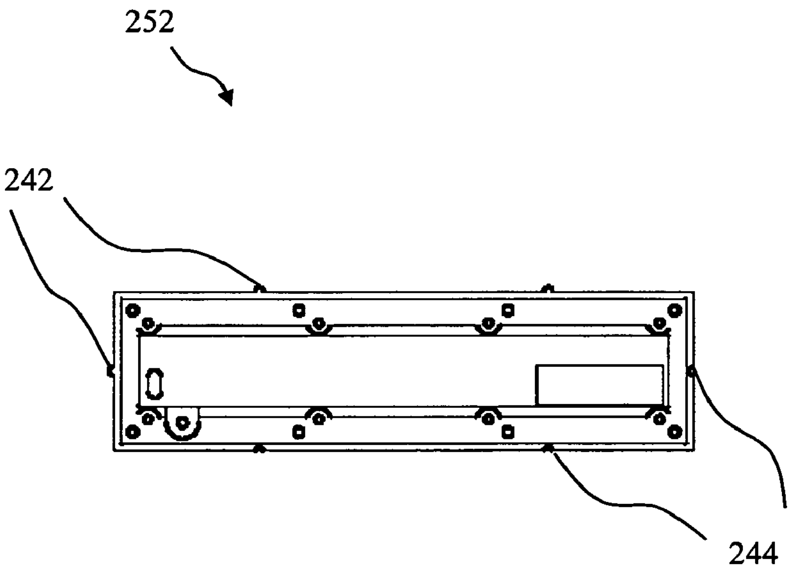
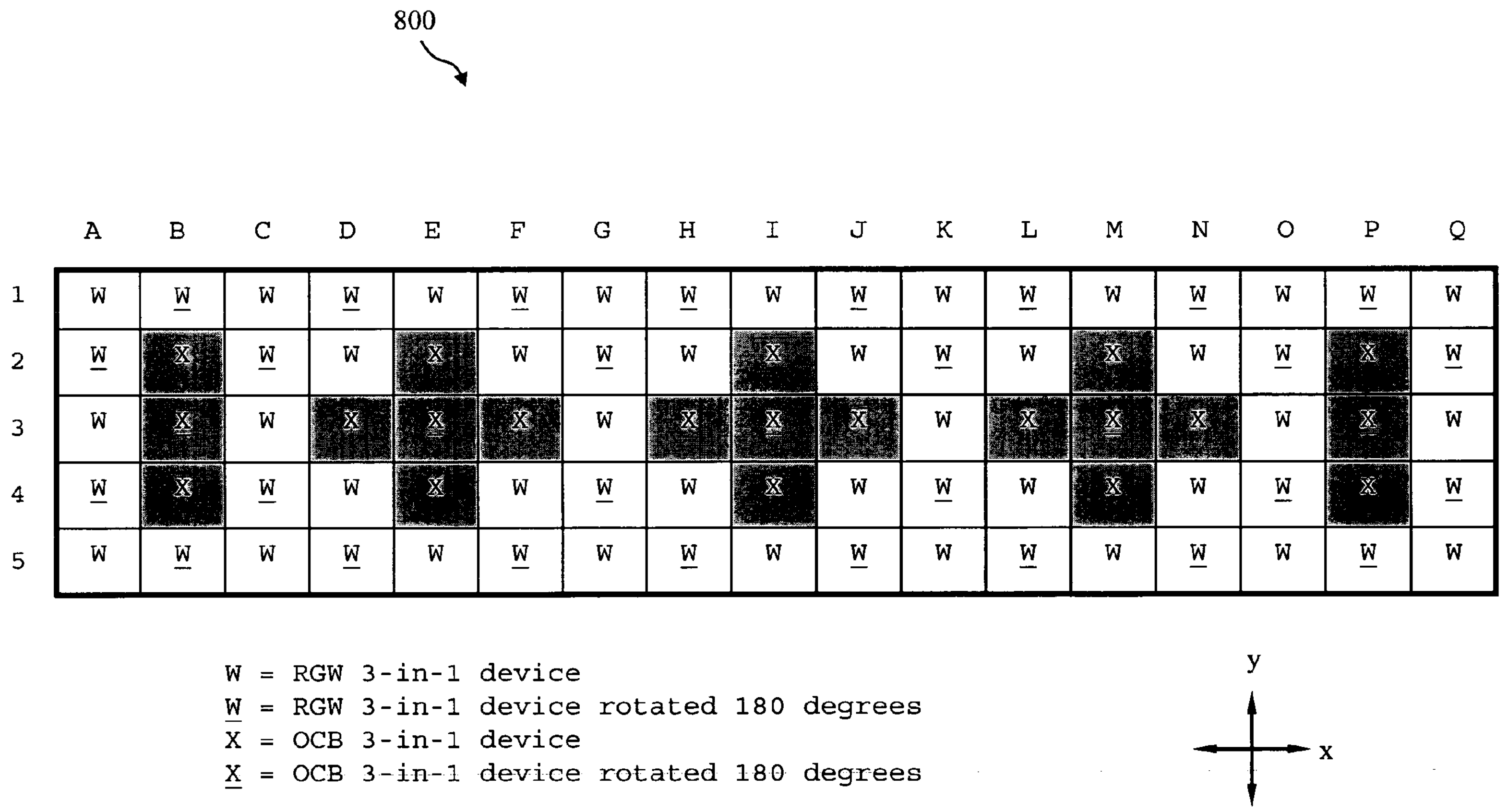


FIG. 10



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W
2	$\underline{W}$	X	$\underline{W}$	W	X	W	$\underline{W}$	W	X	W	$\underline{W}$	W	X	W	$\underline{W}$	X	$\underline{W}$
3	W	$\underline{X}$	W	X	$\underline{X}$	X	W	X	$\underline{X}$	X	W	X	$\underline{X}$	X	W	$\underline{X}$	W
4	$\underline{W}$	X	$\underline{W}$	W	X	W	$\underline{W}$	W	X	W	$\underline{W}$	W	X	W	$\underline{W}$	X	$\underline{W}$
5	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W	$\underline{W}$	W

W = RGW 3-in-1 device
$\underline{W}$ = RGW 3-in-1 device rotated 180 degrees
X = OCB 3-in-1 device
$\underline{X}$ = OCB 3-in-1 device rotated 180 degrees

FIG. 11

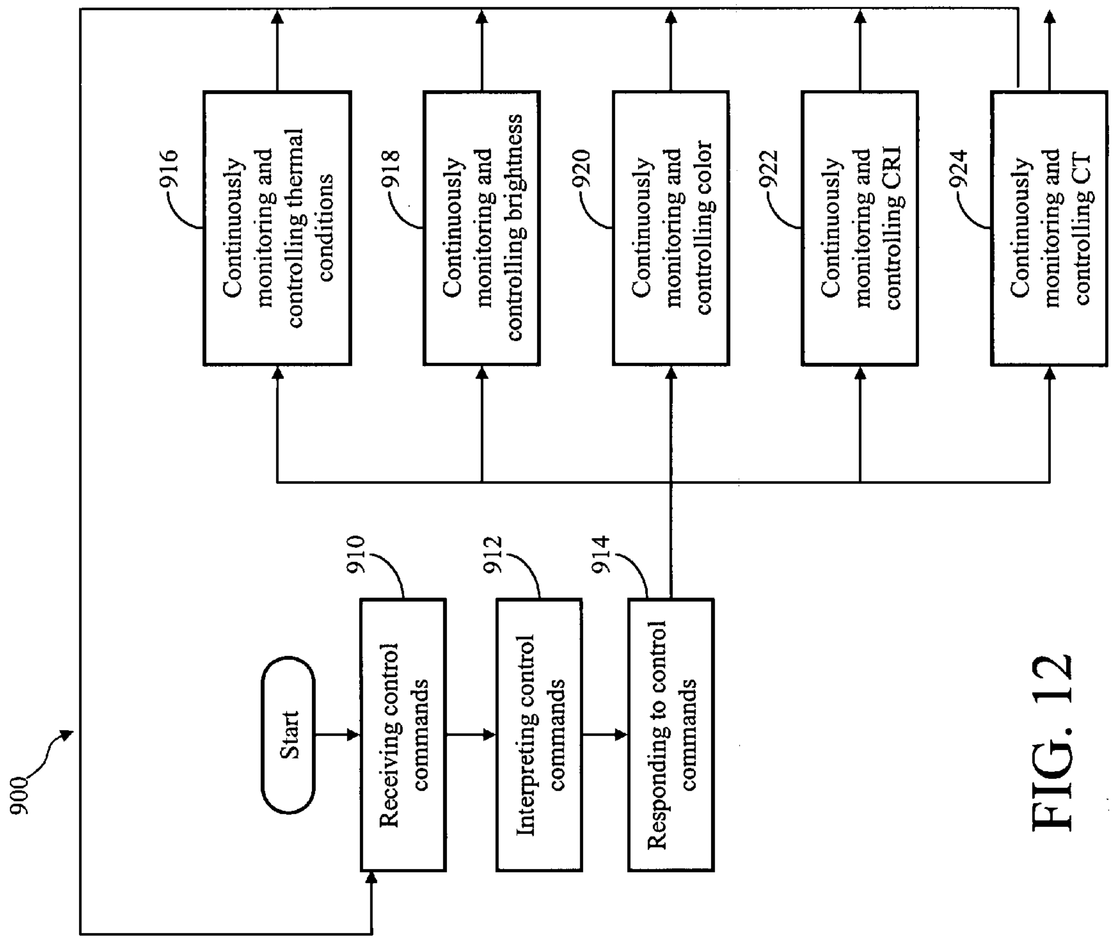

900
Start
910
Receiving control commands
912
Interpreting control commands
914
Responding to control commands
916
Continuously monitoring and controlling thermal conditions
918
Continuously monitoring and controlling brightness
920
Continuously monitoring and controlling color
922
Continuously monitoring and controlling CRI
924
Continuously monitoring and controlling CT

FIG. 12

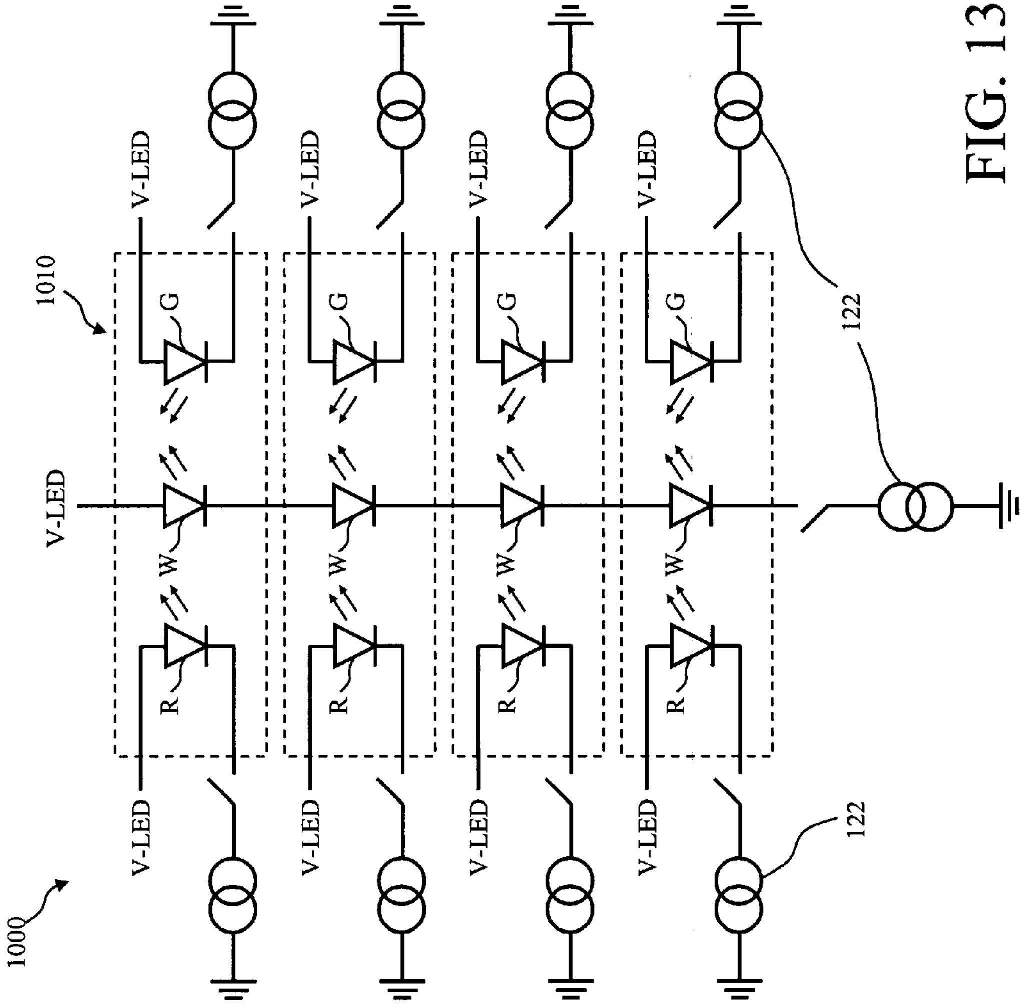

1000
1010
V-LED
V-LED
V-LED
V-LED
V-LED
V-LED
V-LED
V-LED
V-LED
R
W
G
R
W
G
R
W
G
R
W
G
122
122

FIG. 13

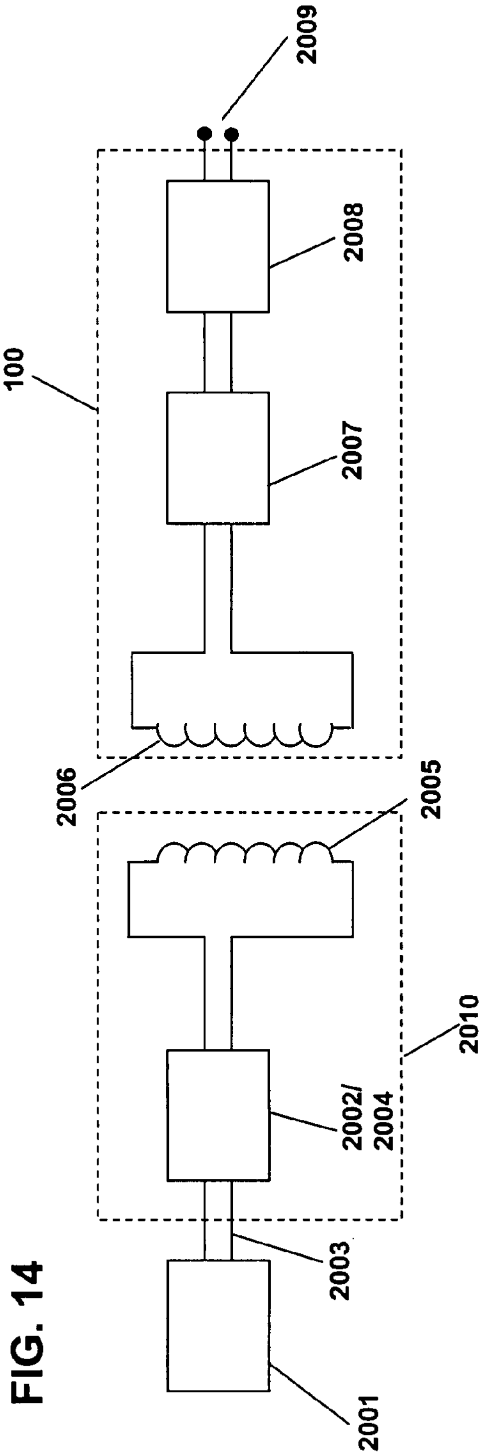


FIG. 14

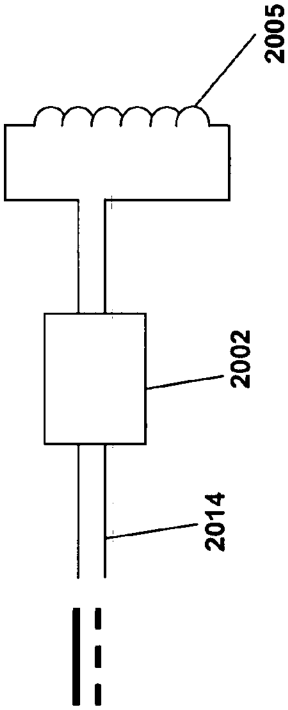


FIG. 15

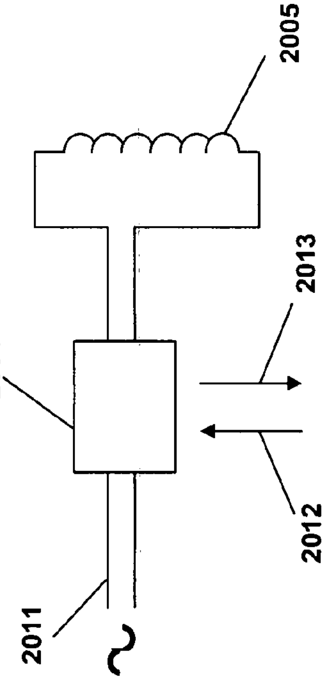


FIG. 16

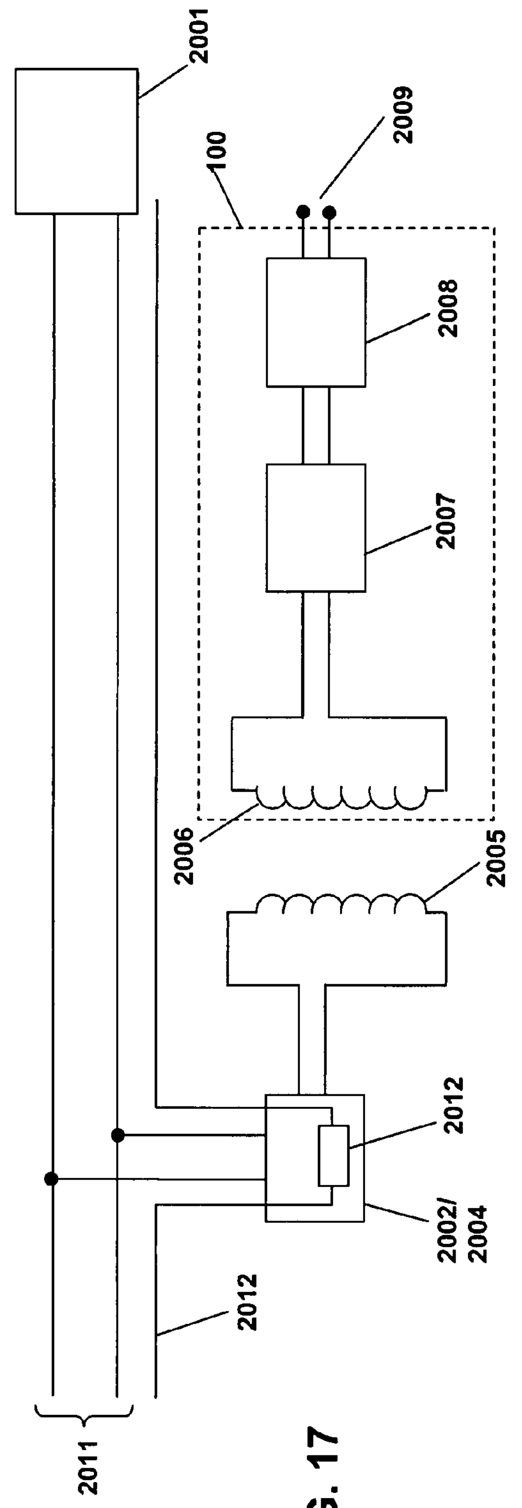


FIG. 17

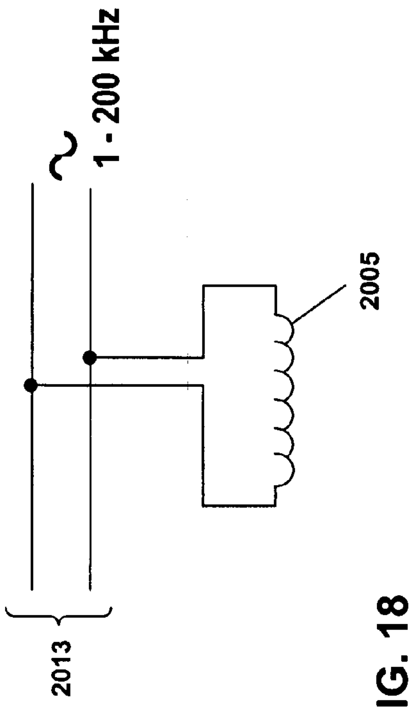


FIG. 18

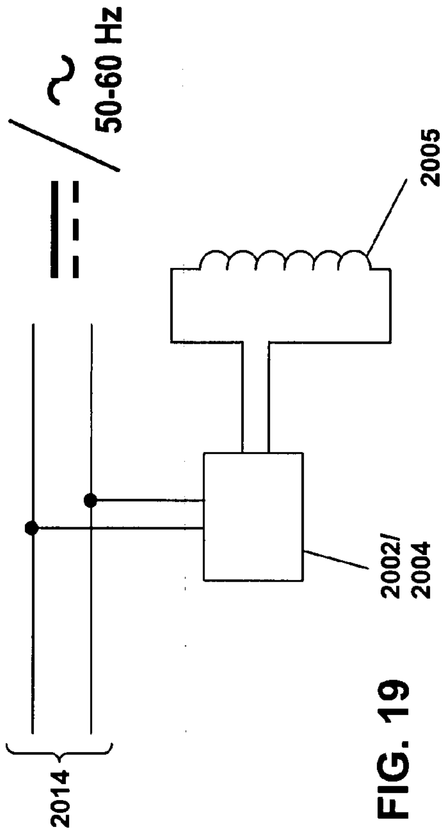


FIG. 19

LED LIGHTING THAT HAS CONTINUOUS AND ADJUSTABLE COLOR TEMPERATURE (CT), WHILE MAINTAINING A HIGH CRI

FIELD OF THE INVENTION

[0001] The present invention generally relates to the field of illumination devices formed of light-emitting diodes. In particular, the present invention is directed to a modular, standalone, and multi-functional electronic and mechanical platform for light-emitting diode (LED) lighting applications that has continuous and adjustable color temperature (CT) and can maintain a high CRI.

BACKGROUND

[0002] An LED is a semiconductor device that can produce an emission with a brilliant color and high efficiency in spite of its small size. In the past, LEDs have been applied mainly to display devices. For that reason, the use of LEDs as a light source for illumination purposes has not yet been researched and developed sufficiently.

[0003] In order to break into the lighting market, it is beneficial to present the market an illumination product that provides compelling motivation for use thereof. In particular, today's LED solutions in the lighting market are very application-specific and/or excessively cumbersome, i.e., too complex mechanically and technically, to compel their general use.

[0004] For example, in a typical LED solution, the LEDs therein dictate one or more printed circuit board designs and then the printed circuit board designs dictate the mechanical design. The resulting product is, therefore, limited because its design is suited for one application only, such as for a desk lamp or a ceiling light only. Its design specifications are not suitable for other lighting applications. Alternatively, a generic LED lighting product may be provided that is formed of separate components that require assembly, such as separate electronics, separate power supplies, separate cabling, and a separate control system. Consequently, such a generic design is difficult to sell to a customer because it requires a highly technical understanding thereof, which is overwhelming to the customer. Because it is not understood easily by a non-technical individual (e.g., customer), this generic LED lighting product is not likely to become a standard in the illumination market. For these reasons, a need exists for a generic LED lighting product that provides ease of use for a non-technical individual and that is multi-functional, in order to provide a LED lighting product that is accepted readily into the lighting market and that is suitable for multiple lighting applications.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. **1** illustrates a chromaticity diagram;

[0006] FIG. **2**A illustrates a schematic diagram of a multiple-in-1 (MIO) LED (3-in-1) device in accordance with an embodiment of the invention;

[0007] FIG. **2**B illustrates a top view of the MIO-LED (3-in-1) device as depicted in FIG. **2**A;

[0008] FIG. **2**C illustrates a cross-sectional view of the MIO-LED (3-in-1) device as depicted in FIG. **2**A;

[0009] FIG. **3**A illustrates a schematic diagram of a MIO-LED (4-in-1) device of another embodiment of the invention.

[0010] FIG. **3**B illustrates a top view of the MIO-LED (4-in-1) device of as depicted in FIG. **3**A; and

[0011] FIG. **3**C illustrates a cross-sectional view of the MIO-LED (4-in-1) device as depicted in FIG. **3**A;

[0012] FIG. **4** illustrates a functional block diagram of an LED module system, in accordance with the invention;

[0013] FIG. **5** illustrates a perspective front view of a modular LED device, which houses the LED module system of FIG. **4**;

[0014] FIG. **6** illustrates a perspective back view of the modular LED device, which houses the LED module system of the present invention;

[0015] FIGS. **7**A and **7**B illustrate a first and second perspective view, respectively, of a PCB assembly for forming the LED module system of the present invention;

[0016] FIG. **8** illustrates an exploded view of modular LED device, which houses the LED module system of the present invention;

[0017] FIG. **9** illustrates a cross-sectional view of modular LED device, which houses the LED module system of the present invention;

[0018] FIG. **10** illustrates a front view of a housing/heatsink of the modular LED device that houses the LED module system of the present invention;

[0019] FIG. **11** illustrates an exemplary LED configuration of the LED module system of the present invention;

[0020] FIG. **12** illustrates a flow diagram of a method of operating the LED module system of the present invention; and

[0021] FIG. **13** illustrates an LED circuit for increased efficiency.

[0022] FIG. **14** illustrates a configuration of the modular LED device where a secondary coupler provides power thereto via induction.

[0023] FIG. **15** shows a configuration where a DC power source provides power to an external primary coupler.

[0024] FIG. **17** shows an inductive power supplier; **2010** may incorporate additional circuitry configured to detect the position of the light source in a string.

[0025] FIG. **18** shows a common rail that supplies high frequency power directly to a primary coupler.

[0026] FIG. **19** shows a common rail that supplies mains power (AC) or DC power indirectly to a primary coupler.

SUMMARY OF SOME EMBODIMENTS OF INVENTION

[0027] One embodiment of the present invention is a Light Emitting Diode, LED, module lighting system (**100**) comprising:

- **[0028]** two or more multiple-in-one, MIO, LED devices (**120**), each MIO-LED device (**120**) comprising at least three LEDs (**212**, **214**, **216**, **312**, **314**, **316**, **318**) together in a housing body (**210**, **310**) wherein:
  - **[0029]** a) the light emitting parts of said at least three LEDs are encapsulated in and connected by a solid, transparent material, and
  - **[0030]** b) said at least three LEDs (**212**, **214**, **216**, **312**, **314**, **316**, **318**) each emit a different colour of light, whereby each colour is selected from the group consisting of blue, red, green yellow, orange, cyan, purple, white and magenta,
- **[0031]** a digital signal processor, DSP (**112**), and
- **[0032]** a digital to analogue converter, DAC, (**124**) for each LED (**212**, **214**, **216**, **312**, **314**, **316**, **318**) or a set of LEDs, wherein the system is configured so that signals from the DSP (**112**) regulate the overall colour and

brightness of light emitted by the MIO-LED devices (**120**) by controlling the power applied to each LED (**212**, **214**, **216**, **312**, **314**, **316**, **318**) or set of LEDs through the DAC.

[0033] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the solid, transparent material comprises at least one phosphor material (**228**) that is activated by light emitted from one or more of said LEDs, so producing light having a spectrum broader than that emitted by said activating LED.

[0034] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the phosphor material (**228**) comprises one or more of the phosphors listed in Tables 1, 2 or 3, or an optical brighteners.

[0035] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein:

[0036] at least one LED in a MIO-LED (**120**) device emits blue light, and

[0037] phosphor material (**228**) is yttrium-aluminum-garnet, YAG, phosphor.

[0038] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein said DSP (**112**) is configured to control the power applied to each LED (**212**, **214**, **216**, **312**, **314**, **316**, **318**) or set of LEDs, such that the colour and brightness of light emitted is the same for each MIO-LED device (**120**).

[0039] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising a pulse width modulator, PWM, switch (**126**) for controlling the power applied to each LED (**212**, **214**, **216**, **312**, **314**, **316**, **318**) or a set of LEDs, using signals from the DSP (**112**).

[0040] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the DSP is configured to control the PWM switch (**126**) to adjust the power supplied to two or more LEDs of the same colour present in separate MIO-LED devices (**120**), when said two or more LEDs emit different shades of said colour.

[0041] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the DSP is configured to control the DAC to adjust the power supplied to two or more LEDs of the same colour present in separate MIO-LED devices (**120**), when said two or more LEDs emit different shades of said colour.

[0042] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein said two or more LEDs of the same colour have not been grouped by binning.

[0043] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising one or more temperature sensors (**130**) configured to provide temperature information of the module to the DSP (**112**).

[0044] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the DSP (**112**) is configured to control of the power applied to each LED (**212**, **214**, **216**, **312**, **314**, **316**, **318**) or set of LEDs of an MIO-LED device (**120**) based on temperature information received from the temperature sensors (**130**), such that the colour and brightness of light emitted from each MIO-LED device (**120**) is maintained where there are changes in temperature.

[0045] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising one or more air cooling fan (**260**), configured to cool at least some of the LEDs (**212**, **214**, **216**, **312**, **314**, **316**, **318**).

[0046] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein said DSP (**112**) is configured to control power to the fan (**260**) based on temperature information received from the temperature sensors (**130**). Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the DSP (**112**) is configured, such that the colour and brightness of light emitted from each MIO-LED device (**120**) is maintained where there are changes in temperature.

[0047] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising one or more network interfaces (**114**) configured to signals to the DSP (**112**), allowing an external control.

[0048] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising one or more IR sensors (**114**) configured provide to signals to the DSP (**112**), allowing an external control.

[0049] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising a power supply (**116**) configured to supply power to the LEDs (**212**, **214**, **216**, **312**, **314**, **316**, **318**) and other components.

[0050] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein said power supply (**116**) has a plurality of DC voltage outputs, each providing a different voltage to match the rating voltage for a colour-emitting LED (**212**,**214**, **216**, **312**,**314**, **316**, **318**).

[0051] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein said power supply (**116**) is configured to adapt it's output level, for at least one colour dependent, on the required light output, controlled by the DSP.

[0052] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising a secondary induction coupler (**2005**), which provides power to the power supply (**116**) by electromagnetic induction from a primary induction coupler (**2006**).

[0053] Another embodiment of the present invention is an LED module system (**100**) as described above, further comprising a memory storage device (**128**) configured to provide data to the DSP (**112**) regarding colour and/or brightness compensation information of each MIO-LED device (**120**).

[0054] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the DSP (**112**) is configured to continuously monitor the power supplied to each LED (**212**, **214**, **216**) in order to maintain the colour and brightness provided by each MIO-LED device (**120**).

[0055] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the colour and brightness are maintained according to relationships between current and colour behavior, and/or light output vs. temperature data.

[0056] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein said relationships are stored as data within storage device (**128**) where present.

[0057] Another embodiment of the present invention is an LED module system (**100**) as described above, wherein the colour temperature, CT, of the emitted light is adjustable.

[0058] Another embodiment of the present invention is an LED module system (**100**) as described above, capable of emitting light that provides a high colour rendition index, CRI.

[0059] Another embodiment of the present invention is a modular LED device (**201**) comprising a housing and one or more LED module systems (**100**) as described above, whereby:

[0060] an array of MIO-LED devices (**120**) is arranged as a light emitting surface

[0061] a mechanical means to stack two or more modular LED devices (**201**) is provided.

[0062] Another embodiment of the present invention is a modular LED device (**201**) as described above, whereby said mechanical stacking means aligns the respective light emitting surfaces to project light towards the same direction.

[0063] Another embodiment of the present invention is a modular LED device (**201**) as described above, wherein the housing comprises an interfacing material which can be used to make contact with other heat conductive materials, so as to transfer heat from the device more easily.

DETAILED DESCRIPTION OF THE INVENTION

[0064] Unless defined otherwise, all technical and scientific terms Used herein have the same meaning as is commonly understood by one of skill in the art. All publications referenced herein are incorporated by reference thereto. All United States patents and patent applications referenced herein are incorporated by reference herein in their entirety including the drawings.

[0065] The articles "a" and "an" are used herein to refer to one or to more than one, i.e. to at least one of the grammatical object of the article. By way of example, "a cooling fan" means one cooling fan or more than one cooling fan.

[0066] Throughout this application, the term "about" is used to indicate that a value includes the standard deviation of error for the device or method being employed to determine the value.

[0067] The recitation of numerical ranges by endpoints includes all integer numbers and, where appropriate, fractions subsumed within that range (e.g. 1 to 5 can include 1, 2, 3, 4 when referring to, for example, a number of cooling fans, and can also include 1.5, 2, 2.75 and 3.80, when referring to, for example, measurements). The recitation of end points also includes the end point values themselves (e.g. from 1.0 to 5.0 includes both 1.0 and 5.0)

[0068] The present invention relates to a generic LED lighting product that provides ease of use for a non-technical individual and that is multi-functional and suitable for multiple lighting applications. In particular, a modular LED device of the present invention may be utilized as a standalone lighting device. Alternatively, the modular LED device of the present invention may be utilized as a universal and generic building block for forming lighting devices for any lighting application. In particular, a lighting device may be formed of an easily configured arrangement of multiple modular LED devices of the present invention.

[0069] Reference is made in the description below to the drawings which exemplify particular embodiments of the invention; they are not at all intended to be limiting. The skilled person may adapt the device and substituent components and features according to the common practices of the person skilled in the art.

[0070] FIG. **4** illustrates a functional block diagram of an LED module system **100**, in accordance with the invention. LED module system **100** is the electrical design of a modular LED device that provides a generic building block that is easy to use and suitable for multiple lighting applications. LED module system **100** preferably includes an LED circuit **110**, a digital signal processor (DSP) **112**, a network interface **114**, and a power supply **116**. LED circuit **110** further includes an LED array **118** that is formed of a plurality of "multiple-in-one"-LED (MIO-LED) devices **120** (e.g., MIO-LED devices **120-1** to **120**-n), a plurality of current sources **122** (e.g., current sources **122-1** to **122**-n), at least one digital-to-analog converter (DAC) **124**, a plurality of pulse-width modulation (PWM) switches **126** (e.g., PWM switches **126-1** to **126**-n), at least one storage device **128**, one or more temperature sensors **130**, and an infrared (IR) sensor **132**. A suggested configuration connecting the components of LED module system **100** is shown in FIG. **4**.

[0071] LED array **118** of LED circuit **110** may be any array configuration of LED devices, such as an array of MIO-LED devices **120**. Example LED configurations include, but are not limited to, 15×3, 16×4, 17×4, 17×5, and 18×5 arrays.

Multiple-In-One-LED Device (MIO-LED Devices)

[0072] Each MIO-LED device **120** (e.g., each MIO-LED device **120-1** through **120**-n) of LED array **118** may comprise a multitude of LEDs i.e. it may be a 'multiple-in-one' LED-device (MIO-LED). A MIO-LED device, is a device having a number of LEDs in one housing body e.g. 3 LEDs (3-in-1), 4 LEDs (4-in-1), 5 LEDs (5-in-1), 6 LEDs (6-in-1), 7 or more LEDs etc. Of the LEDs present in a MIO-LED device, any three of them each may emit a different colour of light, whereby each colour is selected from the group consisting of blue, red, green yellow, orange, cyan, purple, white and magenta,

[0073] The LEDs used in the present invention can be any kind of LED known in the art, capable of providing light at the required wavelength or within a defined band of wavelengths. LEDs typically comprise semiconducting material impregnated, or doped, with impurities to create a p-n junction. Such LEDs behave like diodes insofar as current flows from the p-side, or anode, to the n-side, or cathode, but not in the other direction. The wavelength of light emitted, depends on the band gap energy of the materials forming the p-n junction. Where the semiconducting material is an inorganic substance or mixture, it can be any suitable for the wavelength required e.g. aluminum gallium phosphide (AlGaP) for green light or gallium phosphide (GaP) for red, yellow or green light, zinc selenide (ZnSe) for blue light. Such combination of semiconducting materials are known in the art. Where the semiconducting material is an organic substance or mixture (i.e. producing an OLED), it can be any suitable for the wavelength required. Such organic substances are known in the art. The term LED used herein covers light emitting semiconductors which are formed of inorganic or organic materials.

[0074] Generally, the quality of white light produced by light sources for illumination purposes is expressed in terms of a colour rendition index (CRI) value. More specifically, light sources, such as LEDs, of the same color can vary widely in the quality of light that is emitted. One light source may have a continuous spectrum, while the other light source emits light in a few narrow bands only of the spectrum. Therefore, a useful way to determine the quality of a light source is its CRI, which serves as a quality distinction between light sources emitting light of the same color. The highest CRI attainable is 100. CRI is a method of describing the effect of a light source on the color appearance of objects, compared with a reference light source of the same color temperature. Additionally, CT is a simplified way to characterize the spectral properties of a light source. Low CT implies warmer (more yellow/red) light, while high CT implies a colder (more blue) light. The standard unit for color temperature is Kelvin (K). For example, daylight has a rather low CT near dawn (approximately 3200K) and a higher CT around noon (approximately 5500K). With this in mind, the use of the MIO-LED devices **120** in an LED array **118** provides a LED module system **100** and associated modular LED devices (FIGS. **5** through **10**) with a continuous, uniform, and adjustable CT range (e.g., 3200 K to 9500 K) while maintaining a high CRI (e.g., 90 or greater) for lighting applications.

[0075] The MIO-LED device has high CRI values for lighting applications, such as, for example, overhead lighting in a room or outdoor area lighting. Because a light source emits radiant energy that is relatively balanced in all visible wavelengths will appear white to the eye, the LED devices of the present invention provide multiple LEDs e.g., red, green and blue, in one package, which allows color mixing in order to provide an appropriate white light source for illumination purposes that, additionally, has the ability to provide CT tracking.

[0076] In particular, the MIO-LED devices of the present invention may utilize at least one phosphor material for converting coloured light (e.g. red, green blue) into broader spectrum light, such as, for example, white light. A phosphor material is any material that is activated by light (e.g. blue, ultraviolet, red, green) produced by an LED, so producing broader spectrum light, such as, for example, white light. Broader spectrum light, is light which has a wider bandwidth compared with the activating light i.e. the LED. Preferably a blue LED is provided in combination with phosphor material for producing white light.

[0077] The phosphor material may be disposed over the other LEDs of the MIO-LED device; in doing so, it provides a mechanism for diffusing the light emitted by the LED, which renders the LED a surface-emitter rather than a point-emitter device and is, thus, more suited for general illumination purposes. The phosphor material need not be limited to the LED, but can be disposed over any transparent part of any casing or housing. Furthermore, the MIO-LED devices of the present invention have a high CRI (e.g., >90) over a continuous, uniform, and adjustable CT range of, for example, 3200 K to 9500 K.

[0078] FIG. **1** illustrates a chromaticity diagram **101**, which is provided as a reference for the discussion to follow with regard to the MIO-LED devices of the present invention. As is well known, a chromaticity diagram, such as chromaticity diagram **101**, is a triangular-shaped line that connects the chromaticities of the spectrum of colors. In the case of chromaticity diagram **101**, this line defines a color triangle **111**. The curved line within color triangle **111** of chromaticity diagram **101** shows where the color of the spectrum lie and is called the spectral locus. In particular, a black body curve **113** is the spectral locus for white light. Combinations of colors, such as shades of blue, green, yellow, orange, and red, along black body curve **113** mix and produce white light. The colour temperatures along black body curve **113** are indicated in Kelvin. Furthermore, FIG. **1** shows the range of CTs along the length of black body curve **113**. For example, the end of black body curve **113** that is near the blue area indicates a CT of 10000K (cool light) and approaches infinity. By contrast, the end of black body curve **113** that is near the red area indicates a CT of 2500K (warm light) and approaches zero. Additionally, those skilled in the art will understand that the more colors of the spectrum that are present with sufficiently high energy levels within a white light source, the higher the CRI of the white light source and, thus, the higher the quality of the white light.

[0079] According to one aspect of the invention, a MIO-LED device comprises three or more LEDs **212**, **214**, **216**, **312**, **314**, **316**, **318** (FIGS. **2**A to **3**C) together in a housing body **210**, **310** wherein

[0080] a) the light emitting parts of at least three LEDs are encapsulated in and connected by a solid, transparent material,

[0081] c) said at least three LEDs (**212**, **214**, **216**, **312**, **314**, **316**, **318**) each emit a different colour of light, whereby each colour is selected from the group consisting of blue, red, green yellow, orange, cyan, purple, white and magenta.

[0082] The solid, transparent material may comprise a rigid material or may comprise a non-rigid material (e.g. with gel-like properties). Examples of suitable solid, transparent materials include, for example, epoxy and silicon. The solid transparent material may enclose the light emitting parts; this may mean that all the light emitted passes through the solid transparent material, and no light may escape elsewhere. The solid transparent material may connect the light emitting parts; this may mean that the light emitting parts contact a common, continuous, solid transparent material.

[0083] The solid transparent material may be blended with a quantity of phosphor material **228** which comprises one or more phosphors activated by light emitted from one or more of the encapsulated LEDs, so producing light which has a wider spectrum compared with the activating light i.e. the LED, as mentioned above. Examples of suitable phosphor material **228** include yttrium-aluminum-garnet phosphor (YAG-phosphor) which is activated by blue light.

[0084] Examples of phosphors which may be present in a phosphor material **228** include, but are not limited to any indicated in Tables 1, 2 or 3 compounds, where the colour of light emitted is also given in brackets. Phosphors may be blended so as to give the necessary broad emission spectrum.

TABLE 1

Phosphor materials useful according to the invention
ZnS: Ag + (Zn,Cd)S: Ag (P4) (white), Y_2O_2S: Eu + Fe_2O_3 (P22R) (red), ZnS: Cu,Al (P22G) (green), ZnS: Ag + Co-on-Al_2O_3 (P22B) (blue), Zn_2SiO_4: Mn (P1, GJ), (yellowish-green (525 nm)), ZnS: Ag,Cl or ZnS: Zn (P11, BE), (blue (460 nm)), (KF,MgF_2): Mn (P19, LF) (yellow (590 nm)), (KF,MgF_2): Mn (P26, LC), (orange (595 nm)), (Zn,Cd)S: Ag or (Zn,Cd)S: Cu (P20, KA), (yellow-green), ZnO: Zn (P24, GE) (green (505 nm)), (Zn,Cd)S: Cu,Cl (P28, KE)

TABLE 1-continued

Phosphor materials useful according to the invention
(yellow), ZnS: Cu or ZnS: Cu,Ag (P31, GH), y(ellowish-green), MgF_2: Mn (P33, LD) (orange (590 nm)), $(Zn,Mg)F_2$: Mn (P38, LK), (orange (590 nm)) Zn_2SiO_4: Mn,As (P39, GR) (green (525 nm)), ZnS: Ag + (Zn,Cd)S: Cu (P40, GA) (white), Gd_2O_2S: Tb (P43, GY) (yellow-green (545 nm)), Y_2O_2S: Tb (P45, WB), (white (545 nm)), Y_2O_2S: Tb, (green (545 nm)), $Y_3Al_5O_{12}$: Ce (P46, KG) (green (530 nm)), $Y_3(Al,Ga)_5O_{12}$: Ce (green (520 nm)), Y_2SiO_5: Ce (P47, BH) (blue (400 nm)), $Y_3Al_5O_{12}$: Tb (P53, KJ) (yellow-green (544 nm)), $Y_3(Al,Ga)_5O_{12}$: Tb (yellow-green (544 nm)), ZnS: Ag,Al (P55, BM) (blue (450 nm)), $InBO_3$: Tb (yellow-green (550 nm)), $InBO_3$: Eu (yellow (588 nm)), ZnS: Ag (blue (450 nm)), ZnS: Cu,Al or ZnS: Cu,Au,Al (green (530 nm)), Y_2SiO_5: Tb (green (545 nm)), (Zn,Cd)S: Cu,Cl + (Zn,Cd)S: Ag,Cl (white), $InBO_3$: Tb + $InBO_3$: Eu (amber), (ZnS: Ag + ZnS: Cu + Y_2O_2S: Eu (white), $InBO_3$: Tb + $InBO_3$: Eu + ZnS: Ag (white)

TABLE 2

Phosphor materials useful according to the invention.
$(Ba,Eu)Mg_2Al_{16}O_{27}$ (blue), $(Ce,Tb)MgAl_{11}O_{19}$ (green), $(Y,Eu)_2O_3$(red), $(Sr,Eu,Ba,Ca)_5(PO_4)_3Cl$ (blue), $(La,Ce,Tb)PO_4$ (green), Y_2O_3: Eu (red (611 nm)), $LaPO_4$: Ce,Tb (green (544 nm)), $(Sr,Ca,Ba)_{10}(PO_4)_6Cl_2$: Eu (blue (453 nm)), $BaMgAl_{10}O_{17}$: Eu,Mn (blue-green (456/514 nm)), $(La,Ce,Tb)PO_4$: Ce,Tb (green (546 nm)), Zn_2SiO_4: Mn (green (528 nm)), Zn_2SiO_4: Mn,Sb_2O_3(green (528 nm)), $Ce_{0.67}Tb_{0.33}MgAl_{11}O_{19}$: Ce,Tb (green (543 nm)), Y_2O_3: Eu(III) (red (611 nm)), $Mg_4(F)GeO_6$: Mn ((red (658 nm)), $Mg_4(F)(Ge,Sn)O_6$: Mn (red (658 nm)), $MgWO_4$ (pale blue (473 nm)), $CaWO_4$ (blue (417 nm)), $CaWO_4$: Pb (scheelite, blue (433 nm)), $(Ba,Ti)_2P_2O_7$: Ti (blue-green (494 nm)), $Sr_2P_2O_7$: Sn, blue (460 nm), $Ca_5F(PO_4)_3$: Sb (blue (482 nm)), $Sr_5F(PO_4)_3$: Sb,Mn (blue-green (509 nm)), $BaMgAl_{10}O_{17}$: Eu,Mn (blue (450 nm)), $BaMg_2Al_{16}O_{27}$: Eu(II) (blue (452 nm)), $BaMg_2Al_{16}O_{27}$: Eu(II),Mn(II) (blue (450 + 515 nm)), $Sr_5Cl(PO_4)_3$: Eu(II) (blue (447 nm)), $Sr_6P_5BO_{20}$: Eu (blue-green (480 nm)), $(Ca,Zn,Mg)_3(PO_4)_2$: Sn (orange-pink (610 nm)), $(Sr,Mg)_3(PO_4)_2$: Sn (orange-pinkish white (626 nm)), $CaSiO_3$: Pb,Mn (orange-pink (615 nm)), $Ca_5F(PO_4)_3$: Sb,Mn (yellow), $Ca_5(F,Cl)(PO_4)_3$: Sb,Mn (warm white to cool white or blue or daylight), $(Ca,Sr,Ba)_3(PO_4)_2Cl_2$: Eu (blue (452 nm)), 3 $Sr_3(PO_4)_2 \bullet SrF_2$: Sb,Mn (blue (502 nm)), $Y(P,V)O_4$: Eu (orange-red (619 nm)), $(Zn,Sr)_3(PO_4)2$: Mn (orange-red (625 nm)), Y_2O_2S: Eu (red (626 nm)), $(Sr,Mg)_3(PO_4)_2$: Sn(II) (orange-red (630 nm)), 3.5 $MgO \bullet 0.5\ MgF_2 \bullet GeO_2$: Mn (red (655 nm)), $Mg_5As_2O_{11}$: Mn (red (660 nm)), $Ca_3(PO_4)_2 \bullet CaF_2$: Ce,Mn, (yellow (568 nm)), $SrAl_2O_7$: Pb (ultraviolet (313 nm)), $BaSi_2O_5$: Pb (ultraviolet (355 nm)), $SrFB_2O_3$: Eu(II) (ultraviolet (366 nm)), SrB_4O_7: Eu (ultraviolet (368 nm)), $MgGa_2O_4$: Mn(II), (blue-green), $(Ce,Tb)MgAl_{11}O_{19}$ (green).

TABLE 3

Phosphor materials useful according to the invention.
Gd_2O_2S: Tb (P43) (green (peak at 545 nm)), Gd_2O_2S: Eu (red (627 nm)), Gd_2O_2S: Pr (green (513 nm)), Gd_2O_2S: Pr,Ce,F (green (513 nm)), Y_2O_2S: Tb (P45) (white (545 nm)), Y_2O_2S: Tb (P22R) (red (627 nm)), Y_2O_2S: Tb (white (513 nm)), Zn(0.5)Cd(0.4)S: Ag (HS) (green (560 nm)), Zn(0.4)Cd(0.6)S: Ag (HSr) (red (630 nm)), $CdWO_4$ (blue (475 nm)), $CaWO_4$ (blue (410 nm)), $MgWO_4$ (white (500 nm)), Y_2SiO_5: Ce (P47) (blue (400 nm)), $YAlO_3$: Ce (YAP) (blue (370 nm)), $Y_3Al_5O_{12}$: Ce (YAG) (green (550 nm)), $Y_3(Al,Ga)_5O_{12}$: Ce (YGG) (green (530 nm)), CdS: In (green (525 nm)), ZnO: Ga (blue (390 nm)), ZnO: Zn (P15) (blue (495 nm)), (Zn,Cd)S: Cu,Al (P22G) (green (565 nm)), ZnS: Cu,Al,Au (P22G) (green (540 nm)), ZnCdS: Ag,Cu (P20) (green (530 nm)), ZnS: Ag (P11) (blue (455 nm)), anthracene (blue (447 nm)), plastic (EJ-212, blue (400 nm)), Zn_2SiO_4: Mn (P1) (green (530 nm)), ZnS: Cu (GS) (green (520 nm)), CsI: Tl (green (545 nm)), $^6LiF/ZnS$: Ag (ND) (blue (455 nm)), $^6LiF/ZnS$: Cu,Al,Au (NDg) (green (565 nm)).

[0085] Examples of other phosphors include, but are not limited to optical brighteners, which act act as UV-sensitive phosphors with close-to-zero afterglow. Usually they are organic compounds, typically found in detergents. In order to obtain a broader emission spectrum and the desired colours, the above mentioned phosphors may be mixed according to the practices of the skilled person.

[0086] Thus, the arrangement of a MIO-LED that includes phosphor material **228** allows the production of white light by virtue of the interaction between the phosphor and the activating LEDs (e.g. blue emitting LED). The inventors have also found, it also allows adjustment of the CT by virtue of the non-activating LEDs present (e.g. red or yellow when the phosphor is YAG-phosphor). Furthermore, the phosphor has an efficient diffusing effect on the light output, meaning the light is mixed at very close distance; the consequence is a higher CRI compared with separate, non-diffused LEDs.

[0087] A further advantage is that the non-activating LEDs can be used to adjust minor differences in CT between any two MIO-LED devices; the consequence is that binning (the practice by manufacturers of testing each LED for flux, colour, voltage and placing each in a bin for given tolerances) can be eliminated.

[0088] According to one aspect of the invention, the paths of light emitted by said at least three LEDs (**212**, **214**, **216**, **312**, **314**, **316**, **318**) at least partly overlap. This requires the said LEDs to be in close proximity to eachother. Preferably, the LEDs are arranged so their paths of light overlap, such that their individual colours are blended when the activated MIO-LED viewed at a distance of no less than 50 mm. This viewing distance may be reduced to no less than 5 mm when the diffusing phosphor is present.

3 in 1 Embodiment of a MIO-LED Device

[0089] FIG. **2**A illustrates a schematic diagram of a MIO-LED (3-in-1) device **200** in accordance with an embodiment of the invention. LED (3-in-1) device **200** includes a device housing body **210** within which is arranged three LEDs **212**, **214**, **216**. The housing body **210** positions the LEDs so the paths of light emitted thereby at least partly overlap. It also provide an appropriate projection direction for the paths of light. 3-in-1 LED device **200** further includes a plurality of leads **218** that are arranged on the perimeter of device housing body **210**. More specifically, the cathode and anode of LED **212** is electrically connected to a first pair of leads **218**, respectively; the cathode and anode of LED **214** is electrically connected to a second pair of leads **218**, respectively; the cathode and anode of LED **216** is electrically connected to a third pair of leads **218**, respectively; as shown in FIG. **2**A.

[0090] FIG. **2**B illustrates a top view (not to scale) of MIO-LED (3-in-1) device **200** of an embodiment of the invention. FIG. **2**C illustrates a cross-sectional view (not to scale) of MIO-LED (3-in-1) device **200**, taken along line A-A of FIG. **1**B. FIGS. **2**B and **2**C show that LEDs **212**, **214**, and **216** of MIO-LED (3-in-1) device **200** are arranged physically in a cavity formed by the sidewalls and floor of housing body **210**. In particular, LEDs **212**, **214**, and **216** are mounted on respective pedestals **222** that are arranged within housing body **210**, as shown in FIGS. **2**B and **2**C. Additionally, LEDs **212**, **214**, and **216** are encapsulated within housing body **210** of 3-in-1 LED device **200** by use of a solid, transparent material **224**, which material encloses and connects the light emitting parts.

[0091] With continuing reference to FIGS. **2**A, **2**B, and **2**C, MIO-LED (3-in-1) device **200** is formed by a 1×3 array of LEDs. Housing body **210** may be formed of any suitably rigid, lightweight, thermally-conductive, and electrically non-conductive material, such as, but not limited to, molded plastic or ceramic. Housing body **210** provides a cavity within which LEDs **212**, **214**, and **216** are mounted. The cavity may be formed by a set of sidewalls and a floor, as shown in FIGS. **2**B and **2**C. The length, width, and height of housing body **210** may vary. An example length, width, and height may be 5.5×5.5×2.5 millimeters (mm), respectively. Leads **218** are formed of electrically conductive material, such as, but not limited to, a gold plated copper alloy. Leads **218** may be any standard lead structure, such as a surface-mount type lead. On a given side of housing body **210**, the spacing between leads **218** may be, for example, 1.78 mm.

[0092] LED **212**, LED **214**, and LED **216** may be standard LED die devices of various application- or user-defined color combinations that produce white light. In particular, the combination of the individual colors emitted by LED **212**, LED **214**, and LED **216**, respectively, mix to produce a white light and, thereby, render 3-in-1 LED device **200** a white illumination device. In a preferred embodiment, at least one of LED **212**, LED **214**, and LED **216** is a blue LED, while the color of the remaining two LEDs may be vary (e.g., various combinations of red, green, blue, yellow, orange, cyan, and/or magenta). The placement of the blue LED within the arrangement of LED **212**, LED **214**, and LED **216** is normally inconsequential e.g. it may be flanked by LED of other colours, or may flank one of the other LEDs. In one example, LED **212** is a red LED, LED **214** is a blue LED, and LED **216** is a green LED. In another example, LED **212** is a yellow LED, LED **214** is a blue LED, and LED **216** is a cyan LED. 3-in-1 LED device **200** is not limited to the examples cited above, other color combinations are possible.

[0093] LED **212**, LED **214**, and LED **216** may each be mounted on a pedestal **222**, respectively, which reside within a cavity formed by housing body **210**. Each pedestal **222** is formed of an electrically conductive material, such as, but not limited to, copper, aluminum, silver, or gold. By use of each pedestal **222**, electrically conductive wires (not shown) are bonded between the anode and cathode of each LED and its respective pair of leads **218** and, thus, an electrical connection is formed therebetween, as shown in FIG. **2**A. Pedestals **222** and, thus, LED **212**, LED **214**, and LED **216** may be placed on a pitch of, for example, 0.95 mm.

[0094] LED **212**, LED **214**, and LED **216** are encapsulated within housing body **210** by use of solid, transparent material **224**, which material encloses and connects the light emitting parts. The solid, transparent material **224** may comprise, for example, a transparent epoxy. The epoxy may be blended with and a quantity of phosphor material **228** (e.g., YAG-phosphor). The combination of phosphor material with a blue LED produces a high-brightness white light source. Epoxy, into which YAG-phosphor is blended, may be a transparent epoxy resin. Additionally, the percent of YAG-phosphor that is present within solid, transparent material **224** may be, for example, between 0 and 5%. One example manufacturer of high-brightness while LEDs by use of YAG-phosphor in combination with a blue LED is Nichia Corporation (Japan). YAG is commonly used as the down-conversion phosphor in white LEDs, as YAG phosphor can be excited by the radiation from blue LEDs, which produces white light. An example supplier of powder phosphors consisting of micron- or submicron-size particles is Nitto Denko Technical Corporation (Carlsbad, Calif.). Furthermore, another benefit of the presence of the phosphor material **228** (e.g., YAG-phosphor) within the solid, transparent material **224** is that the phosphor material **228** acts to diffuse the light that is emitted by LED **212**, LED **214**, and LED **216**. As a result, 3-in-1 LED device **200** is converted from a point-emitting light source to a surface-emitting light source, which is more suited for functional lighting applications.

[0095] With continuing reference to FIGS. **2**A, **2**B, and **2**C, various combinations of colored LEDs within MIO-LED (3-in-1) device **200** for producing a white light source that is suitable for functional lighting applications are disclosed, e.g., red (R), green (G), blue (B), yellow (Y), orange (O), cyan (C), purple (P) and/or magenta (M). In each case, 3-in-1 LED device **200** may include at least one blue LED that reacts with the YAG (i.e., B+YAG) to produce white light. In the case wherein 3-in-1 LED device **200** includes R, G, and B+YAG, the combination thereof provides the mechanism by which the CT (see FIG. **1**) may be determined and adjusted, as compared with standard light sources. The addition of R and G provides a shift along black body curve **112** of chromaticity diagram **100** of FIG. **1** further toward the blue area, as compared with an LED with B+YAG alone. Furthermore, by varying the current that is supplied to LED **212**, LED **214**, and LED **216**, the colors of the LEDs may change slightly, which then has a positive effect on producing a higher CRI. In another example configuration, MIO-LED (3-in-1) device **200** may include Y, P, and B+YAG, to produce white light and to provide yet a further shift along black body curve **112** toward the blue area, as compared with B+YAG alone or R, G, and B+YAG. In yet another example configuration, 3-in-1 LED device **200** may include Y, C, and B+YAG to produce a device with a yet higher CRI because this combination adds even more spectra to the light.

[0096] In all instances of MIO-LED (3-in-1) device **200**, adding two colors, such as R and G, to B+YAG adds more light spectra, which increases the CRI and, thus, increases the light quality.

4 in 1 Embodiment of a MIO-LED Device

[0097] FIG. **3**A illustrates a schematic diagram of a MIO-LED (4-in-1) device **300** of a second embodiment of the invention. MIO-LED (4-in-1) device **300** includes a housing body **310** within which is arranged four LEDs **312**, **314**, **316**, **318**. MIO-LED (4-in-1) device **300** further includes a plurality of leads **320** that are arranged on the perimeter of housing body **310**. More specifically, the cathode and anode of LED **312** may be electrically connected to a first pair of leads **320**, respectively; the cathode and anode of LED **314** may be electrically connected to a second pair of leads **320**, respectively; the cathode and anode of LED **316** may be electrically connected to a third pair of leads **320**, respectively; the cathode and anode of LED **318** may be electrically connected to a fourth pair of leads **320**, respectively; as shown in FIG. **3**A.

[0098] FIG. **3**B illustrates a top view (not to scale) of MIO-LED (4-in-1) device **300** of the second embodiment of the invention. FIG. **3**C illustrates a cross-sectional view (not to scale) of the MIO-LED (4-in-1) device **300**, taken along line B-B of FIG. **3**B. FIGS. **1**B and **1**C show that LEDs **312**, **314**, **316**, and **318** of MIO-LED (4-in-1) device **300** are arranged physically in a cavity formed by the sidewalls and floor of housing body **310**. In particular, LEDs **312**, **314**, **316**, and **318** are mounted on respective pedestals **322** that are arranged within housing body **310**, as shown in FIGS. **3**B and **3**C. Additionally, LEDs **312**, **314**, **316**, and **318** are encapsulated within housing body **310** of 4-in-1 LED device **300** by use of a solid, transparent material **324**, which may be formed, for example, from a transparent epoxy; the epoxy might be blended, with a quantity of YAG-phosphor **328**, as shown in FIG. **3**C.

[0099] With continuing reference to FIGS. **3**A, **3**B, and **3**C, MIO-LED (4-in-1) device **300** may be formed by a 1×4 array of LEDs. Alternatively, MIO-LED (4-in-1) device **300** may be formed by a 2×2 array of LEDs. Any arrangement is within the scope of the invention. Housing body **310** may be formed of any suitably rigid, lightweight, thermally-conductive, and electrically non-conductive material, such as, but not limited to, molded plastic or ceramic. Housing body **310** provides a cavity within which LEDs **312**, **314**, **316**, and **318** are mounted. The cavity is formed by a set of sidewalls and a floor, as shown in FIGS. **3**B and **3**C. The length, width, and height of housing body **310** may vary. An example length, width, and height may be 6.5×5.5×2.5 mm, respectively. Leads **320** are formed of electrically conductive material, such as, but not limited to, a gold plated copper alloy. Leads **320** may be any standard lead structure, such as a surface-mount type lead. On a given side of housing body **310**, the spacing between leads **320** may be, for example, 1.78 mm.

[0100] LED **312**, LED **314**, LED **316**, and LED **318** may be standard LED die devices of various application- or user-defined color combinations that produce white light. In particular, the combination of the individual colors emitted by LED **312**, LED **314**, LED **316**, and LED **318**, respectively, mix to produce a white light and, thereby, render 4-in-1 LED device **300** a white illumination device. In a preferred embodiment, at least two of LED **312**, LED **314**, LED **316**, and LED **318** are blue LEDs, while the color of the remaining two LEDs may be vary (e.g., various combinations of red, green, blue, yellow, orange, cyan, and/or magenta). The placement of the two blue LEDs within the physical 1×4 or 2×2 array arrangement of LED **312**, LED **314**, LED **316**, and LED **318** is inconsequential. In one example, LED **312** is a red LED, LED **314** is a blue LED, LED **316** is a blue LED, and LED **318** is a green LED i.e. red may be adjacent to blue, which is adjacent to another blue, which is adjacent to green. In another example, LED **312** is a yellow LED, LED **314** is a blue LED, LED **316** is a blue LED, and LED **318** is a cyan LED i.e. yellow may be adjacent to blue, which is adjacent to another blue, which is adjacent to cyan. MIO-LED (4-in-1) device **300** is not limited to the examples cited above; other colour combinations and arrangements are possible.

[0101] LED **312**, LED **314**, LED **316**, and LED **318** may each be mounted on pedestals **322**, respectively, which reside within the cavity formed by housing body **310**. Each pedestal **322** may be formed of an electrically conductive material, such as, but not limited to, copper, aluminum, silver, or gold. By use of each pedestal **322**, electrically conductive wires (not shown) may be bonded between the anode and cathode of each LED and its respective pair of leads **320** and, thus, an electrical connection is formed therebetween, as shown in FIG. **3**A. Pedestals **322** and, thus, LED **312**, LED **314**, LED **316**, and LED **318** may be placed on a pitch of, for example, 0.95 mm.

[0102] LED **312**, LED **314**, LED **316**, and LED **318** are may be encapsulated within housing body **310** by use of a solid, transparent material **324**, which material encloses and connects the light emitting parts. Solid, transparent material **324** may comprise, for example, a blend of transparent epoxy (e.g., epoxy **326**); the solid, transparent material epoxy might be blended with a quantity of phosphor material (e.g., YAG-phosphor **328**). The combination of phosphor material with a blue LED produces a high-brightness white light source. Epoxy **326** and YAG-phosphor **328** of solid, transparent material **324** are substantially identical in form and function to epoxy and YAG-phosphor of the solid, transparent material **224**, as described in FIGS. **2**A, **2**B, and **2**C. Again, a benefit of the presence of phosphor material (e.g., YAG-phosphor **328**) within epoxy is that the phosphor material acts to diffuse the light that is emitted by LED **312**, LED **314**, LED **316**, and LED **318**. As a result, MIO-LED (4-in-1) device **300** is converted from a point-emitting light source to a surface-emitting light source, which is more suited for functional lighting applications.

[0103] Because blue LEDs tend to have a shorter lifetime than R and G, the presence of two blue LEDs in the MIO-LED device allows the user to activate one blue LED only and then activate the second blue LED only when the first blue LED begins to fail. Alternatively, both blue LEDs may be activated simultaneously, but at a reduce power level, which prolongs their lifetime. In both cases, a technique is provided for prolonging the overall lifetime of the device due to failure of the blue LED. An additional benefit of including two blue LEDs is that in the event that, should the solid-transparent material discolor (e.g. turn brown) over time, activating the second blue LED can help overcome the losses due to the aged transparent material. This technique can also be applied to other LEDs dependent on their lifetime characteristics.

[0104] In the case wherein MIO-LED (4-in-1) device **300** includes R, G, B+YAG, and B+YAG, the combination thereof provides the mechanism by which the CT may be determined and adjusted, as compared with standard light sources. Furthermore, by varying the current that is supplied to LED **312**, LED **314**, LED **316**, and LED **318**, the colors of the LEDs may change slightly, which then has a positive effect on producing a higher CRI. Additionally, 4-in-1 LED device **300** or higher (>4-in-1) MIO-LED device provides a yet further expanded (multi-spectra) device as compared with 3-in-1 LED device **200**, which results in a yet higher CRI.

[0105] In another example configuration, MIO-LED (4-in-1) device **300** includes R, G, O and B+YAG, which provides a yet further expanded (multi-spectra) device for achieving a yet higher CRI. Because all three LEDs of MIO-LED (3-in-1) device **200** and MIO-LED (4-in-1) device **300** are activated simultaneously, their power rating may be reduced for a certain illumination as compared with one white LED only that produces the same illumination. For example, each LED may dissipate 250 watts only as compared to one device that dissipates 1 to 5 watts. Therefore, the thermal management system (not shown) for MIO-LED devices of the present invention (e.g. MIO-LED (3-in-1) device **200** or MIO-LED (4-in-1) device **300**) may be simplified as compared with high-power LEDs. Additionally, the combination of multiple (e.g., three or four) LEDs in a single package produces a surface-emitter device, instead of a point-emitter device.

[0106] In the case wherein MIO-LED (4-in-1) device **300** includes R, G, B+YAG, and B+YAG, the combination thereof provides the mechanism by which the CT may be determined and adjusted, as compared with standard light sources. Furthermore, by varying the current that is supplied to LED **312**, LED **314**, LED **316**, and LED **318**, the colors of the LEDs may change slightly, which then has a positive effect on producing a higher CRI. Additionally, 4-in-1 MIO-LED device **300** (or other >4-in-1 MIO-LED device) provides a yet further expanded (multi-spectra) device as compared with 3-in-1 LED device **200**, which results in a yet higher CRI.

[0107] Separate leads for each LED of MIO-LED (3-in-1) device **200** and MIO-LED (4-in-1) device **300** (or other >4-in-1 MIO-LED device) allows individual control of forward bias voltage (e.g., R=2 volts, B and G=4 volts). However, the present invention is not limited to separate leads. Alternatively, 3-in-1 LED device **200** and MIO-LED (4-in-1) device **300** may include a common lead to drive multiple LEDs when operating, for example, in a common anode or common cathode configuration.

[0108] Because the human eye is very sensitive to variations in white light, combining R and G with B+YAG provides a mechanism for obtaining a high CRI. Compensating the individual color differences between the MIO-LEDs B+YAG alone provides a broad range of about 75% CRI, but adding R and G to B+YAG allows, for example, the device to be adjusted to 6900K and held constant. Adding R and G to B+YAG allows compensation to move light along the CT curve (see FIG. **1**). The result is a MIO-LED device (e.g. a MIO-LED (3-in-1) device **200** or MIO-LED (4-in-1) device **300**) of the present invention provide a white light illumination device that has a CT in the range of 3200K to 9500K and a CRI of 90 and above.

Other Embodiments of a MIO-LED Device

[0109] Furthermore, the present invention is not limited to MIO-LED 3-in-1 and 4-in-1 devices, n-in-1 devices are possible. For example, a 6-in-1 device may be formed by use of R, G, B+YAG and Y, C, B+YAG. R, G, B+YAG allows of CT shift toward red only, whereas Y, C, B+YAG further allows a CT shift toward blue (See FIG. **1**). In this example, further adjustability is provided. In all examples of MIO-LED (3-in-1) device **200**, MIO-LED (4-in-1) device **300**, and n-in-1 devices, adding two or more colors, such as R and G, to B+YAG adds more light spectra, which increases the CRI and, thus, increases the light quality. It can also give the user the opportunity to optimize for different lighting requirements.

[0110] Furthermore, in all examples of MIO-LED (3-in-1) device **200**, MIO-LED (4-in-1) device **300**, and n-in-1 devices, the solid, transparent material may be silicon based instead of epoxy based, as the use of silicon may increase the lifetime of the device. Additionally, in all examples of MIO-LED (3-in-1) device **200**, MIO-LED (4-in-1) device **300**, and n-in-1 devices, the LEDs may be replaced with organic LED (OLED) devices to produce a white light source that is suitable for functional lighting applications.

Modules and Methods Incorporating MIO-LEDs

[0111] One embodiment of the present invention is a module **100** that incorporates a plurality of MIO-LED devices as described above. In the following description, reference is made to FIG. **4** which depicts a plurality of MIO-LED devices **120** present in a module **100**. The plurality of MIO-LED devices **120** (e.g. **120-1**) may configured as an LED array **118**. The LED array comprises an arrangement of LEDs, which together project light from the array, combining their light output. The array may comprise columns and rows as depicted in FIG. **5**. However it is not limited to such as arrangement, and may alternatively be arranged, for example, circularly, spirally, irregularly etc.

[0112] The array may comprise, for example, a RGB+YAG MIO-LED (3-in-1) device that is described above. Because the B+YAG LED produces white light, the RGB+YAG MIO-LED device is referred to as the RGW MIO-LED device. In another example, an MIO-LED device **120** of LED array **118** may be an orange, cyan, and blue (OCB) MIO-LED device that is described above. Two or more MIO-LED devices **120** may be different, for example, the array **118** may comprise various combinations of MIO-LED devices described above, such as a combination of RGW and OCB MIO-LED devices. More details of an example LED configuration that includes a combination of two MIO-LED devices are described with reference to FIG. **4**. The MIO-LED devices described may be 3-in-1 devices, i.e. having only three LEDs, or may comprise additional LEDs so forming, for example, a 4-in-1, 5-in-1, 6-in-1 etc. device.

[0113] Current sources **122-1** through **122**-n are associated with MIO-LED devices **120-1** through **120**-n, respectively, and each represents multiple current source devices (e.g. a current source **122** for the R LED, a current source **122** for the

G LED, and a current source **122** for the W LED). Thus, each of the LEDs within each MIO-LED device **120** may have a dedicated current source **122**.

[0114] Current sources **122** may be any commercially available constant current sources that are capable of supplying a constant current, typically in the range of 5 to 80 milliamps (mA), to MIO-LED devices **120**. One example constant current device includes, but is not limited to, the DM132 16-channel PWM-controlled constant current driver, supplied by Silicon Touch Technology Inc. (Taiwan).

[0115] The module **100** of the present invention may comprise a DAC **124** that is connected to the MIO-LED devices **120** so as to control the brightness of each LED, or of a set (e.g. 2, 3, 4, 5, 6 or more) of LEDs therein. Thus, there may be one DAC per LED or one DAC per set of LEDs. Where one DAC **124** controls a set of LEDs, the LEDs in the set may be the same colour. This allows an arrangement a cluster of MIO-LEDs devices (e.g. 2, 3, 4, 5 or 6 or more) is controlled by one DAC **124** for each colour of LED present. For example, where the MIO-LEDs devices in a cluster each contain RGB+YAG LEDs, there may be 3 DACs **124** controlling this cluster, one for each colour present in each MIO-LED device.

[0116] An example of a configuration of the DAC **124** present in an LED circuit **110** is shown in FIG. **4**. The DAC **124** may be any commercially available digital-to-analog converter device. DAC **124** may have, for example, 8-bit, 10-bit, or 12-bit resolution. The digital input of DAC **124** may be provided by DSP **112** and multiple analog outputs of DAC **124** feed respective current sources **122**. As a result, DAC **124** is used for setting the current value of each current source **122** according to the digital input of DAC **124**. LED circuit **110** is not limited to a single DAC **124** that feeds all current sources **122**, as shown in FIG. **4**. Alternatively, LED circuit **110** may include a combination of multiple DACs **124** in order to set the current values of current sources **122**. In one example, DAC device may be, but is not limited to, the AD5308 8-channel DAC, supplied by Analog Devices (Norwood, Mass.).

[0117] Each of the LEDs within MIO-LED device **120** may be connected to a dedicated PWM switch **126** which permits on/off control of the MIO-LED **120** or of each LED therein, using a signal. For example, pulse-width modulation (PWM) switches **126-1** through **126**-n are associated with MIO-LED devices **120-1** through **120**-n, respectively; each may represent multiple PWM switch devices (e.g., a PWM switch **126** for the R LED, a PWM switch **126** for the G LED, and a PWM switch **126** for the W LED). Each PWM switch **126** (e.g., each PWM switch **126-1** through **126**-n) of LED circuit **110** may be an electronic switch, such as a FET switch, that is used to connect or disconnect a given current source **112** from its respective LED via a PWM signal (not shown) that is generated by DSP **112**. As is well known, pulse width modulation is a technique for controlling an analog circuit, such as LED circuit **110**, with the digital outputs of a processor, such as DSP **112**. Each LED within a MIO-LED device **120** may have a dedicated combination of one current source **122** and one PWM switch **126**, which allows individual control of each LED within the MIO-LED device, which is represented by one MIO-LED device **120** in FIG. **4**.

[0118] The PWM switch **126** may be used to dim a MIO-LED device **120**. The technique of PWM dimming is useful, since it allows the colour output of an LED to remain essentially constant as the current is not altered during dimming (only the duration of pulses provided to an LED). However, it is not the most efficient dimming method, since the current supplied to the LED remains the same using PWM dimming even at very low light outputs. The present invention, instead, may employ current dimming. It may overcome the changes in colour output of an MIO-LED device **120** at different currents by characterising a MIO-LED device at various currents. The system may overcome changes in colour output at different currents by altering the relative colour output of each LED within said MIO-LED device **120**. This characterisation may be performed in the factory, and the association between current, colour and light output provided as information held in a memory which the DSP can access. According to one aspect of the invention, dimming is performed using a mixture of PWM control and current control.

[0119] Storage device **128** of LED circuit **110** may be present in a module **100** of the present invention configured to provide data to the DSP **112**. Storage device **128** storage device is connected so as to provide information to a DSP **112** regarding behavior of the module. Example of color information that may stored in storage device **128** includes, but is not limited to, current vs. color behavior and light output vs. temperature. The storage device **128** may be any non-volatile storage medium, such as a random access memory (RAM) device, a programmable read-only memory (PROM) device, or erasable programmable read-only memory (EPROM) device. The storage capacity of storage device **128** is equal to or greater than that required to store color data for each MIO-LED device **120**, which is used for color compensation of each MIO-LED device **120**, as needed, during the operation of LED module system **100**.

[0120] The color data that is stored in a storage device **128** may be determined at the time that the components of LED circuit **110** are assembled (i.e., at manufacture). This color data may be stored within storage device **128** at the time of assembly or, alternatively, stored when LED module system **100** is placed in the field.

[0121] The module **100** of the present invention, may comprise one or more temperature sensors **130** configured to provide data to the DSP **112** as indicated in LED circuit **110**. Temperature sensors **130** are commercially available temperature sensing devices for sensing the operating temperature of the physical instantiation of LED module system **100**, such as a printed circuit board that is associated with LED circuit **110**. In particular, a plurality of temperature sensors **130** may be installed in close proximity to the physical instantiation of LED array **118** and in a distributed fashion with respect to the area consumed by LED array **118**. The outputs of temperature sensors **130** are fed to DSP **112**, in order for DSP **112** to apply color compensation of MIO-LED devices **120** that is based on temperature variations. Additionally, temperature sensors **130** may be used to measure the internal temperature of the packaging (FIGS. **5** to **10**) of LED module system **100**. DSP **112** may use the information from temperature sensors **130** to control cooling mechanisms of the packaging of LED module system **100**, in order to maintain a constant temperature therein. In one example, temperature sensor device may be, but is not limited to, the AD7415 temperature sensor, supplied by Analog Devices (Norwood, Mass.).

[0122] The module **100** of the present invention may comprise one or more IR sensors **132**. The IR sensor may be configured to provide a signal to the DSP **112** as indicated in LED circuit **110**. The IR sensor **132** may be a commercially available IR sensing device for sensing IR signals from a remote control device (not shown), which is used for operating LED module system **100**. A digital output of IR sensor **132** feeds DSP **112**, which interprets and responds to the remote control commands accordingly. One example IR sensor device includes, but is not limited to, the TSOP **341** IR sensor, supplied by Vishay Intertechnology, Inc.(Malvern, Pa.). Remote control functions that are received via IR sensor **132** and interpreted by use of DSP **112** include, but are not limited to, brightness adjustment, individual color adjustment, pattern selection, color temperature selection, CRI selection, and so forth. The remote control device (not shown) may be any commercially available universal remote control unit, such as used with televisions or DVD players. One example remote control unit that is suitable for use with LED module system **100** is the Philips ProntoPRO TSU6000 universal remote control device, supplied by Royal Philips Electronics N.V, (Amsterdam, Netherlands).

[0123] DSP **112** of LED module system **100** may be a general-purpose microprocessor for processing standard microprocessor instructions. DSPs usually support a set of specialized instructions to perform common signal-processing computations quickly. In one example, DSP device may be, but is not limited to, the TI2802 DSP by Texas Instruments (Dallas, Tex.). DSP **112** manages the overall operation of LED module system **100**. Functions that are managed by use of DSP **112** and that provide multi-functionality to LED module system **100** include, but are not limited to, communications control, on/off control of individual MIO-LED devices **120**, on/off control of entire LED array **118**, cooling system control, power management control, variable brightness control (i.e., dimming), variable color control, variable operating efficiency control, and variable CRI control. In doing so, the operations of DSP **112** include, but are not limited to, the following:

[0124] interpreting and responding to control information that is received via IR sensor **132** from a remote control device;

[0125] interpreting and responding to control information that is received via network interface **114** from an external controller device, such as a computer;

[0126] interpreting information that is received from temperature sensors **130**, in order to control a cooling mechanism (not shown); p**0** interpreting information that is received from temperature sensors **130**, in order to apply temperature compensation as needed to LED circuit **110** that is based on information, such as light output vs. temperature data, within storage device **128**; and

[0127] applying color compensation as needed to LED circuit **110** that is based on information, such as current vs. color behavior data, within storage device **128**.

[0128] In performing the above operations, the function of DSP **112** is to calculate constantly the optimal values for controlling the light output of each MIO-LED device **120**. When DSP **112** receives a request for a certain amount of light for a certain color, DSP **112** responds such that LED circuit **110** is optimized for efficiency or for CRI.

[0129] The DSP **112** may be configured so that the CT and brightness of the light emitted from each MIO-LED device **120** is adjusted to be identical. In other words, the DSP **112** may send control signals which adjust the power to the LEDs, such that the CT and brightness of the light emitted from each MIO-LED device **120** is uniform within each module. As mentioned above, the DSP may be configured to maintain the CT and brightness.

[0130] Alternatively, the DSP **112** may be configured to adjust the CT and brightness of the light emitted from each MIO-LED device **120**. This application may be useful when a module **100** is used as part of a monitor for the display of images such as video, static pictures or computer.

[0131] The module **100** of the present invention may comprise one or more Network interfaces **114**. The Network interface **114** may be configured to exchange control signal and data with the DSP **112** as indicated in LED circuit **110**. Network interface **114** of LED module system **100** provides a communications interface between LED module system **100** and an external control device, such as a computer (not shown). The design of network interface **114** may be communication protocol-specific. Alternatively, the design of network interface **114** may support multiple communication protocols.

[0132] Communication protocols that may be supported by network interface **114** include, but are not limited to, Digital Addressable Lighting Interface (DALI); DMX/DMX512 and DVI/HDMI, which are digital video/data protocols; Recommended Standard 232 (RS-232); Recommended Standard 485 (RS-485); Controller Area Network (CAN); Serial Digital Interface (SDI); High Definition Serial Digital Interface (HD SDI); Ethernet; Art-Net Ethernet; ZigBee wireless; and Bluetooth wireless.

[0133] Power supply **116** of LED module system **100** is configured to receive a source of power (e.g. 90-250 VAC, 50-60 Hz), and transform it, if necessary, for supply to the LEDs and other components. The power supply **116** may be a custom switch-mode power supply. As is well known, a switch-mode power supply incorporates power-handling electronic components that are continuously switching on and off with high frequency and, thus, the output voltage is controlled by varying duty cycle, frequency, or a phase of these transitions. The input of the power supply **116** may be an alternating current (AC) voltage (VAC) in the range of 90-264 VAC, 50-60 Hz. For example, the input voltage may be **110** or 220 VAC. Alternatively, input of power supply **116** may be obtained from an electromagnetic induction source as described below. The power supply **116** may be designed to provide, for example, 25 watts and may include a power factor correction (PFC) feature, which is a technique of counteracting the undesirable effects of electric loads that create a power factor (p.f.) that is less than 1. Power supply **116** provides power for all active electronic devices within LED module system **100**. In particular, power supply **116** produces multiple LED voltages (V-LEDs of LED circuit **110**) for powering MIO-LED devices **120**, which includes LEDs of different colors (each color requires a different V-LED voltage). Table 4 below shows example DC voltages that are associated with each LED color.

TABLE 4

Example V-LED voltages

LED color	DC volts
RED	2.5 max
GREEN	3.5 max
WHITE (B + YAG)	3.5 max
BLUE	3.5 max
CYAN	4.0 max
ORANGE	3.3 max

[0134] According to one embodiment, the invention, the voltage output of the power supply **116** is adjustable according to the required power. For example, e.g. a white LED may have a max V-LED voltage of 3.5V specified at 20 mA current. Another LED may have a V-LED of 3.2V specified at 10 mA of current. When optimizing for efficiency, the power supply maybe configured to receive a signal from the DSP to adjust the voltage output, for example, from 3.5V to 3.2V.

[0135] Additionally, power supply **116** may provide power for a cooling fan (shown in FIGS. **6** and **8**) that is associated with the packaging of LED module system **100**. The output voltage for the cooling fan may be, for example, in the range of 2 to 5 volts DC. Alternatively, the DC voltage may be held constant and the fan may be driven using PWM. The power of the fan may thus be regulated. This is advantageous where it is important to maintain efficiency i.e. reduce power input by reducing fan activity, or to reduce noise also by reducing fan activity.

[0136] Additionally, the LED module system **100** may include a rechargeable battery (not shown), which provides power to LED module system **100** of modular LED device **200** in the event that AC power source is lost. It may be charged by power regulator **116** when the power source is present.

[0137] While the use of AC or DC power is mentioned above, the power input to the power supply **116** may be directly or indirectly using electromagetic induction. Thus, the LED module system **100** may include a receiving part for an inductively coupled power. In such a system, an induction coil (secondary coupler), part of LED module system **100**, receives power by induction from an external coil (primary coupler). The external coil may be integrated into a supporting frame for the system. This may allow the LED module system to operate without power cables, so greatly simplifying setting up the system. The power transferred by the inductive arrangement may range from sub 1 Watt (e.g. 100 mW) to hundreds of Watts.

[0138] An implementation of inductive coupling to transfer energy from a power source towards the lighting system is exemplified in FIG. **14**. An external inductive power supplier **2010** comprises a primary coupler **2005** that receives power **2001** from a main source (e.g. mains AC power at 50 Hz, or AC current at 1 to 200 kHz) through cables **2003**. The inductive power supplier **2010** may convert the power **2001** as necessary and provide it to the primary coupler **2005** in a form that can be transmitted wirelessly to a receiving coil (secondary coupler) **2006** that is part of the LED module system **100**. Additional circuitry **2002**, **2004** may be present in the inductive power supplier **2010** to perform the task of, for example, converting the power source **2001** to a high-frequency waveform, and/or to receive/transmit data information utilising the primary coupler **2005**; the inverter **2002** (if necessary), and data modulator and/or demodulator **2004** are respectively indicated in FIG. **14**.

[0139] The LED module system **100** may comprise a secondary coupler **2006** which receives wirelessly power by inductive coupling from the primary coupler **2005**. The power output **2009** is provided directly or indirectly as the input to the power supply **116** described above. Additional circuitry **2007**, **2008** may also be present in the LED module system **100** to control the voltage of the power output **2009**, and/or to add receive/transmit data information utilising the secondary coupler **2006**; the voltage controller **2007**, and data modulator and/or demodulator **2008** are respectively indicated in FIG. **14**.

[0140] The respective primary **2005** and secondary **2006** couplers may have any suitable shape. Some shapes might have advantages for efficiency of the energy transfer and some shapes might be optimised so as to allow easy mounting or clicking of the light source onto the couplers primary. Some coupler shapes may allow a flat panel design of both couplers.

[0141] Besides using the couplings **2005**, **2006** to transfer energy, data transfer may also be exchanged over the couplings **2005**, **2006**. Data transfer may be bidirectional, i.e. both from the LED module system **100** to the power supplier **2010** and vice versa. Data transfer might be implemented using various modulation techniques (e.g. phase shift key modulation). This technique avoids connections (connectors or plugs) between light sources and the power source and data source. Hence the lamp source can be hermetically closed or sealed for e.g. outdoor use to a certain IP protection level.

[0142] The primary coupler **2005** may be integrated within a frame or holding mechanism which mechanically supports the LED module system **100** or housing thereof. The primary coupler **2005** may be included in a cable, possibly connecting more LED module systems **100**, which connects to a power source. Via cabling, a plurality of primary couplers **2005** can be interconnected to form a 2D or 3D shape of light sources.

[0143] As mentioned above, inductive power supplier **2010** may be incorporate additional circuitry **2002** for converting energy to a waveform frequency suitable for power transfer system; an example of this is show shown (FIG. **15**) which depicts an inverter **2002** receiving DC power, which converts it into higher frequency power (e.g. 1 to 200 kHz) for use by the primary coupler **2005**.

[0144] As mentioned above, inductive power supplier **2010** may incorporate additional circuitry **2002** for generating data transfer (unidirectional or bidirectional) **2012**, **2013** if applicable; an example of this is shown (FIG. **16**) which depicts a data modulator and/or demodulator **2008** receiving DC power.

[0145] The inductive power supplier **2010** may be incorporate additional circuitry **2015** configured to detect the position of the light source in a string **2012** (or matrix) of light sources (FIG. **17**).

[0146] As mentioned above, the inductive power supplier **2010** may be powered from traditional mains power (e.g. 120-250 V AC, 50-60 Hz). However, it may alternatively receive power from a high frequency inverter (e.g. 6 to 250V AC, 1-200 kHz). According to one embodiment of the invention, high frequency power for the primary coupler **2001** is separately provided to the inductive power supplier **2010** via a common rail **2013**. Such configuration is indicated in FIG. **18**. According to another aspect of the invention, mains power or DC power is provided to the inductive power supplier **2010** via a common rail **2014**, which power is used to operate the circuitry and the primary coupling via an inverter **2002**. The use of common rails allows several light sources to be conveniently coupled to a plurality of inductive power suppliers **2010**, where by the power source **2001** is available on common rails. Any common rails **2011**, **2013**, **2014**, or cables connecting the inductive power supplier **2010** can be sealed for outdoor use.

[0147] According to one aspect of the invention the common rails **2011**, **2013**, **2014**, connecting the primary coupler **2001** are hermetically sealed outdoor or underwater use.

[0148] By changing the power output of the primary coupler, light emitted by the LED module system **100**, can be controlled. Such control might be in addition to or an alternative to any electronic control already present in the LED module systems **100**.

[0149] The LED module system **100** may incorporate electronics e.g. a voltage controller **2007**, configured to adjust power or voltage or current received from the secondary coupling **2006**. This can be used to compensate for changes in energy received, compensate for tolerances of the coupler and the electronic components, variance in the gap of the wireless coupling.

[0150] The LED module system **100** may incorporate electronics e.g. a data modulator and/or demodulator **2008**, so as to receive digital data from the primary side and may contain electronics so as to transmit data to the primary side as already mentioned above.

[0151] The LED module system **100** may incorporate may contain any IR receiver or transceiver so as to be able adjust the functionality of the light source. This data also might be transmitted to inductive power supplier **2010** for use on a network or to control other light sources in the system.

[0152] The LED module system **100** may incorporate any wireless receiver and/or transmitter to communicate with other light sources or control devices for the lighting system.

[0153] The LED module system **100** may attach to the primary coupler inductive power supplier **2010** part of the inductive power supplier **2010** by a mounting. Such mounting includes a clickable mounting.

[0154] The LED module system **100** may also be hermetically sealed outdoor or underwater application is possible.

[0155] With continuing reference to FIG. **4**, the operation of LED module system **100** may be as follows. DSP **112** receives commands from a remote control device via IR sensor **132** or from an external controller via network interface **114** and, thus, a user activates LED circuit **110**.

[0156] Subsequently, a user selects one or more functions or modes of operation of LED module system **100** and LED circuit **110** is set accordingly. For example, a user selects a desired brightness, color, efficiency, and/or CRI. DSP **112** interprets and responds to the user selections by querying the information in storage device **128** for each MIO-LED device **120** and calculating the required current value for controlling each MIO-LED device **120**. DSP **112** then sets each current source **122** accordingly via DAC **124**. Additionally, DSP **112** monitors continuously temperature data from temperature sensors **130** in order to apply temperature compensation, as needed, and in order to control the cooling system (not shown). Optionally, the correction for achieving uniform color from one MIO-LED device **120** to its neighbors is accomplished digitally via PWM switches **126**, while the general light output of each MIO-LED device **120** is controlled via current sources **122**. Controlling the light output via current allows for maximum operating efficiency. Additionally, by using the correction data that is stored in storage device **128**, peak color rendering and color output levels may be ensured. In summary, the operation of LED module system **100** utilizes the combination of analog LED drive and digital compensation. The electronics of LED module system **100** provides feedback mechanisms by which DSP **112** may calculate and, therefore, adjust, for example, brightness, CRI, and CT.

[0157] FIG. **5** illustrates a perspective front view of a modular LED device **201**, which comprises a housing and an LED module system **100** of FIG. **4**. Modular LED device **201** is the physical instantiation of a modular LED device that provides a generic building block that is easy to use and suitable for multiple lighting applications. Modular LED device **201** may include an LED board **250** upon which is mounted the components of LED circuit **110** of LED module system **100** of FIG. **5**. Modular LED device **201** may further include a housing/heatsink **252**. Housing/heatsink **252** serves as the package for all electrical components of LED module system **100** and facilitates the thermal management system. Additionally, modular LED device **201** may include a set of screws/spacers **254** for fastening LED board **250** to housing/heatsink **252** and, optionally, for optionally attaching one or more optical devices (e.g., lens, filter, diffuser) to the face of LED board **250**. Optionally, the outer face of LED board **250** may include silicon layer, in order to provide a barrier against contamination or water intrusion.

[0158] Also shown in FIG. **5** is a Detail A of a 3-in-1 LED device **256**, which is one example of one MIO-LED device **120** of LED circuit **110** of LED module system **100** of FIG. **1**. FIG. **5** shows that 3-in-1 LED device **256** includes, for example, three LEDs **258**. LEDs **258** may be, for example, RGW or OCB LEDs to form a RGW or OCB MIO-LED device, as described above.

[0159] FIG. **6** illustrates a perspective back view of modular LED device **201**, which comprises a housing and an LED module system **100** of the present invention. FIG. **6** shows that modular LED device **201** further including a set of click points **220** that are installed in housing/heatsink **252**, a cooling fan **260** mounted in the rear of housing/heatsink **252** that is secured by a fan guard **262**, an AC power port **226**, and one or more (e.g., two) I/O ports **264**.

[0160] Referring again to FIGS. **5** and **6**, LED board **250** may be a multi-layer printed circuit board (PCB) for implementing LED circuit **110** of LED module system **100** of FIG. **4**. In particular, the outer face of LED board **250**, as shown in FIG. **5**, is a physical instantiation of LED array **118** of LED circuit **110**, where MIO-LED devices (e.g. 3 in 1) **256** of LED board **250** equate to MIO-LED devices **120** of LED circuit **110**. Mounted on the inner side (not shown) of LED board **250** are the supporting electrical components of LED circuit **110** (e.g., current sources **122**, DAC **124**, PWM switches **126**, storage device **128**, temperature sensors **130**, and IR sensor **132**). In particular, temperature sensors **130** (not visible) are installed in a distributed fashion across the area of LED board **250**.

[0161] Additionally, a small hole (not shown) that is associated with IR sensor **132** is provided within LED board **250**, in order to provide a line-of-sight port for receiving IR signals from a remote control device.

[0162] FIG. **9** illustrates a cross-sectional view of modular LED device **201**, which comprises a housing and the LED module system **100** of the present invention. taken along line A-A of FIG. **2**. FIG. **9** shows PCB assembly **230** as well as mounting plate **238** secured within housing/heatsink **252**. Additionally, FIG. **9** shows that housing/heatsink **252** includes a plurality of cooling fins **240** for providing a large surface area from which to dissipate heat. Furthermore, the outer cooling fins **240** may be tapered at an angle α, such that the portion of housing/heatsink **252** that accommodates LED board **250** has a greater dimension than the opposite portion of housing/heatsink **252**. Angle α may be in the range of, for example, 2 to 15 degrees, with a specific example of 4 degrees. Although a single modular LED device **201** may be used as a standalone lighting device, in the case of an LED lighting device that is formed of a configuration of multiple generic modular LED devices **201**, the tapered sides of modular LED device **201** allow multiple modular LED devices **201** to be assembled one to another with a slight curvature. The tapered modular LED device **201**, therefore, allows its use in a lighting application that requires a curved surface, again demonstrating the multi-functionality of modular LED device **201**.

[0163] FIG. **10** illustrates a front view of a housing/heatsink **252** of modular LED device **201** that houses LED module system **100** of the present invention. In particular, FIG. **10** shows the portion of housing/heatsink **252** that accommodates LED board **250** and mounting plate **238**. FIG. **10** shows that housing/heatsink **252** further includes a set of alignment notches **242** and alignment detents **244** that are arranged along its outer perimeter. Although a single modular LED device **201** may be used as a standalone lighting device, in the case of an LED lighting device that is formed of a configuration of multiple generic modular LED devices **201**, the combination of click points **220** (shown in FIG. **6**), alignment notches **242**, and alignment detents **244** provide mechanisms for easy assembly of modular LED devices **201** to another. For example, alignment notches **242** of one modular LED devices **201** are easily aligned and fitted to alignment detents **244** of a neighboring modular LED devices **201**.

[0164] Likewise, click points **220** of one modular LED devices **201** may easily aligned and fitted to click points **220** of a neighboring modular LED devices **201**. Accordingly, modular LED device **201** provides a universal building block for forming a lighting device for any lighting application.

[0165] Referring again to FIGS. **5** and **6**, housing/heatsink **252** may be formed of a material, such as, but not limited to, aluminum or magnesium, that has high thermal conductivity and that is lightweight. The design of housing/heatsink **252** in combination with cooling fan **260** provides uniform heat transfer throughout modular LED device **201** and, thus, provides uniform heat dissipation. The inner portion (not visible) of housing/heatsink **252** may include built-in airflow guides, in order to distribute effectively the airflow from cooling fan **260** to hotspots within modular LED device **201**. Housing/heatsink **252** may further include clearances for installing the electronics (e.g., in the form of PCBs) that are associated with LED module system **100**, which are shown in more detail in FIGS. **7**A, **7**B, and **8**.

[0166] According to one embodiment of the invention, the housing/heatsink **252** may include an interfacing material which can be used to make contact with other heat conductive materials, so as to transfer heat from the device more easily.

[0167] Referring again to FIGS. **5** and **6**, cooling fan **260** may be a commercially available DC fan that is suitably small to be installed within housing/heatsink **252** and that provides a cubic feet per minute (CFM) of airflow that adequate to cool modular LED device **201** when operating. In one example, cooling fan **260** may be the AFB03505HA fan, supplied by Delta Electronics, Inc. (Fremont, Calif.), which is a 5.50 CFM fan that has a diameter of 35 millimeters (mm). In another example, cooling fan **260** may be the AFB0305MA fan, supplied by Delta Electronics, Inc. (Fremont, Calif.), which is a 3.00 CFM fan that has a diameter of 30 millimeters (mm).

[0168] Cooling fan **260** is recessed and is, thus, flush with the rear surface of housing/heatsink **252** and is secured by a fan guard **262**, as shown in FIG. **6**. In the event that the back of housing/heatsink **252** abuts an obstacle, cooling fan **260** will continue to rotate and draw air from the ends of housing/heatsink **252**. Cooling fan **260** may be completely temperature controlled via the combination of DSP **112** and temperature sensors **130**. Additionally, cooling fan **260** may be turned off in some applications in order to achieve noise reduction and/or to prolong the lifetime of cooling fan **260**. Fan guard **262** may be formed of any lightweight and rigid material, such as molded plastic, and includes clearances for AC power port **226**, and, for example, two I/O ports **264**. AC power port **226** may be a standardized receptacle for connecting the AC input voltage (e.g., 110 or 220 VAC) to the power regulator **116**. I/O ports **264** may be standardized receptacles for connecting communications cables for the various communication protocols that are described in FIG. **4**. In particular, the first I/O port **264** may provide an I/O connection to the electronics of modular LED device **201**, whereas the I/O signals may be passed in a daisy-chain fashion via the second I/O port **264** to another instance of modular LED device **201**. In this way, an LED lighting device may be formed of a configuration of multiple generic modular LED devices **201**.

[0169] Referring again to FIGS. **5** and **6**, modular LED device **201** may be formed of any user-defined array of MIO-LED devices **256** and, thus, its dimensions may vary accordingly. By way of example, FIGS. **5** and **6** illustrate an instance of modular LED device **201** that is formed of a 17×5 array of MIO-LED devices **256**. In this example, modular LED device **201** may have a depth, d, of between 40 and 50 mm (e.g., 44 mm). If MIO-LED devices **256** are installed on a pitch of, for example, 8.94 mm in the x-dimension, x-pitch, the resulting overall length, l, of modular LED device **201** may be, for example, 152 mm. If MIO-LED devices **256** are installed on a pitch of, for example, 8.55 mm in the y-dimension, y-pitch, the resulting overall height, h, of modular LED device **201** may be, for example, 42.75 mm.

[0170] FIGS. **7**A and **7**B illustrate a first and second perspective view, respectively, of a PCB assembly **230** for forming LED module system **100** of the present invention. PCB assembly **230** includes an arrangement of LED board **250** that is mechanically and electrically connected to a drive control board **232**, which is mechanically and electrically connected to a power supply (P/S) board **234** and a network interface board **236**, upon which is installed one or more (e.g., two) I/O connectors **238**.

[0171] Like LED board **250**, drive control board **232**, P/S board **234**, and network interface board **236** may be multilayer PCBs for implementing the electronics of LED module system **100** of FIG. **4**. In particular, drive control board **232** is the physical instantiation of DSP **112** of LED module system **100**, which includes a DSP device and associated circuitry, P/S board **234** is the physical instantiation of power regulator **116** of LED module system **100**, which includes a compact design of a switch-mode power circuit, and network interface board **236** is the physical instantiation of network interface **114** of LED module system **100**, which includes receiver/driver circuitry that is accessed via I/O connectors **238**. Network interface board **236** allows up to **512** modular LED devices to be configured one to another. The mechanical and electrical (e.g., signal I/O and power) connections between LED board **250**, drive control board **232**, P/S board **234**, and network interface board **236** are provided via standard multipin connectors that allow each PCB of PCB assembly **230** to be easily connected and disconnected at will.

[0172] FIG. **8** illustrates an exploded view of modular LED device **201**, which houses LED module system **100** of the present invention. In particular, FIG. **8** shows the assembly of LED board **250**, drive control board **232**, P/S board **234**, network interface board **236**, cooling fan **260**, and fan guard **262** in relation to housing/heatsink **252**. As shown in FIG. **8**, housing/heatsink **252** includes clearance regions, in order to accommodate all elements therein. More details of housing/heatsink **252** are provided with reference to FIGS. **9** and **10**.

[0173] Additionally, FIG. **8** shows that modular LED device **201** includes a mounting plate **238** that abuts the inner side of LED board **250**. Mounting plate **238** serves as the mechanical and thermal interface between LED board **250** and housing/heatsink **252**. The inner surface of LED board **250** is coated with a heat spreading material, such as Gap pad VO Ultra soft 0.125" thickness GPVOUS-0.125-AC-0816 from The Bergquist Company (Chanhassen, Minn.), in order to transfer heat that is generated by the circuitry of LED board **250** to mounting plate **238** and then to housing/heatsink **252**. The combination of LED board **250** and mounting plate **238** is mechanically attached to housing/heatsink **252** via screws/spacers **254** that are shown in FIG. **5**. Mounting plate **238** may be formed of a rigid, lightweight, and thermally conductive material, such as, but not limited to, aluminum or magnesium. A clearance hole within mounting plate **238** accommodates the electrical connector between LED board **250** and drive control board **232**.

[0174] The design of modular LED device **201**, which includes PCB assembly **230**, provides a mechanism by which the electronics may be considered as replaceable.

[0175] More specifically, PCB assembly **230** and, in particular, LED board **250** in combination with mounting plate **238** may be easily removed from the face of modular LED device **201**. Additionally, when LED board **250** in combination with mounting plate **238** is provided as a consumable item, its characterization data and drivers are all inclusive.

[0176] FIG. **11** illustrates an exemplary LED configuration **800** of LED module system **100** of the present invention. By way of example, LED configuration **800** shows a 17×5 array of MIO-LEDs devices. The MIO-LED devices present in configuration **800** are arranged in rows 1 through 5 and in columns A through Q. Additionally, by way of example, the MIO-LEDs devices may be RGW or OCB MIO-LED devices, or a combination of as described above. In particular, FIG. **11** shows a first quantity of RGW MIO-LED devices (W), a second quantity of RGW MIO-LED devices ($\underline{W}$) that are rotated 180 degrees from its neighbors, a first quantity of OCB (3-in-1) MIO-LED devices (X), a second quantity of OCB MIO-LED devices ($\underline{X}$) that are rotated 180 degrees from its neighbors. The presence of OCB MIO-LED devices in combination with RGW MIO-LED devices provides improved CRI control, as compared with the presence of RGW MIO-LED devices only. Additionally, the presence of OCB MIO-LED devices in combination with RGW MIO-LED devices provides improved efficiency, color, and brightness control, as compared with the presence of RGW MIO-LED devices only. Furthermore, alternating the physical orientation of the RGW and OCB MIO-LED devices in relation to their neighbors provides compensation for differences in the perceived color due to differences in viewing angles.

[0177] Example performance specifications for example configurations are as follows.

[0178] 16×4 LED configuration of 64 RGW MIO-LEDs: x-pitch=9.5 mm, y-pitch=10.69, CRI=92%, brightness=800 lm, CT=3200K, power=22 W;

[0179] 16×4 LED configuration of 48 RGW and 16 OCB MIO-LEDs: x-pitch=9.5 mm, y-pitch=10.69, CRI=95%, brightness=700 lm, CT=3200K, power=22 W;

[0180] 17×5 LED configuration of 85 RGW MIO-LEDs: x-pitch=8.94 mm, y-pitch=8.55, CRI=92%, brightness=1100 lm, CT=3200K, power=25 W; and

[0181] 17×5 LED configuration of 64 RGW and 21 OCB MIO-LEDs: x-pitch=8.94 mm, y-pitch=8.55, CRI=95%, brightness=920 lm, CT=3200K, power=25 W.

[0182] FIG. **12** illustrates a flow diagram of a method **900** of operating an LED module system, such as LED module system **100** of the present invention. In particular, the operation of LED module system **100** utilizes the combination of analog LED drive and digital compensation. Method **900** includes, but is not limited to, the following steps.

[0183] At step **910**, DSP **112** of LED module system **100** may receive control commands from a remote control device via IR sensor **132** and/or an external controller, such as a computer, via network interface **114**. Method **900** proceeds to step **912**.

[0184] At step **912**, DSP **112** of LED module system **100** may interpret the control commands based on a set of predetermined commands for which DSP **112** is programmed to recognize. The predetermined commands may relate, for example, to communications control, on/off control of individual MIO-LED devices **120**, on/off control of entire LED array **118**, cooling system control, power management control, variable brightness control (i.e., dimming), variable color control, variable operating efficiency control, and variable CRI control. Method **900** proceeds to step **914**.

[0185] At step **914**, DSP **112** of LED module system **100** may respond to the control commands by executing a set of predetermined program instructions for each respective control command. Method **900** proceeds to steps **916**, **918**, **920**, **922**, and **924**.

[0186] At step **916**, DSP **112** of LED module system **100** may continuously monitor and control the thermal conditions of modular LED device **201**, in order to provide optimal operation. In particular, DSP **112** may interpret information that is received from temperature sensors **130**, in order to apply temperature compensation, as needed, to LED circuit **110** that is based on information, such as light output vs. temperature data, within storage device **128**. Compensation may be applied to LEDs **118** by DSP **112** controlling current sources **122** via DAC **124** and/or DSP **122** controlling PWM switches **126**. Method **900** returns to step **910**.

[0187] At step **918**, DSP **112** of LED module system **100** may continuously monitor and control the brightness of modular LED device **201**, in order to provide optimal operation. In particular, DSP **112** may apply brightness compensation, as needed, to LED circuit **110** that is based on information, such as current vs. color behavior data and light output vs. temperature data, within storage device **128**. Compensation may be applied to LEDs **118** by DSP **112** controlling current sources **122** via DAC **124** and/or DSP **122** controlling PWM switches **126**. Method **900** returns to step **910**.

[0188] At step **920**, DSP **112** of LED module system **100** may continuously monitor and control the color of modular LED device **201**, in order to provide optimal operation. In particular, DSP **112** may apply color compensation, as needed, to LED circuit **110** that is based on information, such as current vs. color behavior data and light output vs. temperature data, within storage device **128**. Compensation may be applied to LEDs **118** by DSP **112** controlling current sources **122** via DAC **124** and/or DSP **122** controlling PWM switches **126**. Method **900** returns to step **910**.

[0189] At step **922**, DSP **112** of LED module system **100** may continuously monitor and control the CRI of modular LED device **201**, in order to provide optimal operation. In particular, DSP **112** may apply CRI compensation, as needed, to LED circuit **110** that is based on information, such as current vs. color behavior data and light output vs. temperature data, within storage device **128**. Compensation may be applied to LEDs **118** by DSP **112** controlling current sources **122** via DAC **124** and/or DSP **122** controlling PWM switches **126**. Method **900** returns to step **910**.

[0190] At step **924**, DSP **112** of LED module system **100** may continuously monitor and control the CT of modular LED device **201**, in order to provide optimal operation. In particular, DSP **112** may apply compensation, as needed, to LED circuit **110** that is based on information, such as current vs. color behavior data and light output vs. temperature data, within storage device **128**. Compensation may be applied to LEDs **118** by DSP **112** controlling current sources **122** via DAC **124** and/or DSP **122** controlling PWM switches **126**. Method **900** returns to step **910**.

[0191] In an alternative circuit arrangement of LED array **118** of LED circuit **110** of FIG. **4** that results in increased efficiency, multiple W LEDs may be driven by a common current source **122**, an example of which is shown with reference to FIG. **13**. FIG. **13** illustrates an LED circuit **1000** for increased efficiency. LED circuit **1000** shows the W (i.e., B+YAG) LEDs of a plurality of MIO-LED devices electrically connected in series and driven by a common current source **122**. By way of example, FIG. **13** shows four MIO-LED (3 in 1) devices **1010**, wherein the W LEDs are electrically connected in series and driven by a common current source **122** and wherein all remaining R and G LEDs are driven by separate current source **122**. In the arrangement of LED circuit **1000**, nine current sources **122** are required, rather than twelve as described reference to LED array **118** of LED circuit **110** of FIG. **4**. The reduced number of current source **122** results in increased device efficiency. The scenario of LED circuit **1000** provides less color and brightness control as compared with each W LED having its own dedicated current source **122**; however, in a static lighting application brightness uniformity is less critical. Additionally, in this scenario the R LED and G LED, which are driven individually, may be used to provide color compensation.

1. A Light Emitting Diode (LED) module lighting system comprising:

two or more multiple-in-one (MIO) LED devices, each MIO-LED device comprising at least three LEDs together in a housing body, wherein:

light emitting parts of said at least three LEDs are encapsulated in and connected by a solid, transparent material, and

said at least three LEDs each emit a different colour of light, whereby each colour is selected from the group consisting of blue, red, green yellow, orange, cyan, purple, white and magenta;

a digital signal processor (DSP); and

a digital to analogue converter (DAC) for each LED or a set of LEDs, wherein the system is configured so that signals from the DSP regulate the overall colour and brightness of light emitted by the MIO-LED devices by controlling the power applied to each LED or set of LEDs through the DAC.

2. LED module lighting system according to claim **1**, wherein the solid, transparent material comprises at least one phosphor material that is activated by light emitted from one or more of said LEDs, so producing light having a spectrum broader than light emitted by said activating LED.

3. LED module lighting system according to claim **2**, wherein the phosphor material comprises one or more of the phosphors or optical brighteners, wherein the one or more phosphors comprise:

ZnS:Ag+(Zn,Cd)S:Ag (P4) (white), Y_2O_2S :Eu+Fe_2O_3 (P22R) (red), ZnS:Cu,AI (P22G) (green), ZnS:Ag+Co-on-AI_2O_3 (P22B) (blue), Zn_2SiO_4:Mn (P1, GJ), (yellowish-green (525 nm)), ZnS:Ag,CI or ZnS:Zn (P11, BE), (blue (460 nm)), (KF,MgF_2):Mn (P19, LF) (yellow (590 nm)), (KF, Mg F_2): Mn (P26, LC), (orange (595 nm)), (Zn,Cd)S:Ag or (Zn,Cd)S:Cu (P20, KA), (yellow-green), ZnO:Zn (P24, GE) (green (505 nm)), (Zn,Cd)S:Cu,CI (P28, KE) (yellow), ZnS:Cu or ZnS:Cu,Ag (P31, GH), yellowish-green), MgF_2:Mn (P33, LD) (orange (590 nm)), (Zn,Mg)F_2:Mn (P38, LK), (orange (590 nm)) Zn_2SiO_4:Mn,As (P39, GR) (green (525 nm)), ZnS:Ag+(Zn,Cd)S:Cu (P40, GA) (white), Gd_2O_2STb (P43, GY) (yellow-green (545 nm)), Y_2O_2SiTb (P45, WB), (white (545 nm)), Y_2O_2STb, (green (545 nm)), $Y_3AI_5O_{12})Ce$ (P46, KG) (green (530 nm)), $Y_3(AI_1Ga)_5O_{12})Ce$ (green (520 nm)), Y_2SiO_5:Ce (P47, BH) (blue (400 nm)), $Y_3AI_5O_{12}$:Tb (P53, KJ) (yellow-green (544 nm)), $Y_3(AIGa)_5O_{12}Tb$ (yellow-green (544 nm)), $ZnSiAg_1AI$ (P55, BM) (blue (450 nm)), $InBO_3Tb$ (yellow-green (550 nm)), $InBO_3IEu$ (yellow (588 nm)), ZnSiAg (blue (450 nm)), $ZnSiCu_1AI$ or $ZnSiCu_1AuAI$ (green (530 nm)), Y_2SiO_5Tb (green (545 nm)), (Zn,Cd)S:Cu,CI+(Zn,Cd)S:Ag,CI (white), $lnBO_3Tb$+$lnBO_3$:Eu (amber), (ZnS:Ag+ZnS:Cu+Y_2O_2S:Eu (white), $lnBO_3Tb$+$lnBO_3$:Eu+ZnS:Ag (white), $(Ba_1Eu)Mg_2AI_{16}O_{27}$ (blue), $(Ce_1Tb)MgAI_{11}O_{19}$ (green), $(Y_1Eu)_2O_3$ (red), $(Sr,Eu,Ba,Ca)_5(PO_4)CI$ (blue), $(La_1Ce_1Tb)PO_4$ (green), Y_2O_3IEu (red (611 nm)), $LaPO_4ICe_1Tb$ (green (544 nm)), $(Sr,Ca,Ba)_{10}(PO_4)_6CI_2$:Eu (blue (453 nm)), $BaMgAI_{10}O_{17}IEu_1Mn$ (blue-green (456/514 nm)), $(La_1Ce_1Tb)PO_4ICe_1Tb$ (green (546 nm)), Zn_2SiO_4IMn (green (528 nm)), $Zn_2SiO_4IMn_1Sb_2O_3$ (green (528 nm)), $Ce_{06z}Tb_{0\ s3}MgAI_{11}O_{19}ICe_1Tb$ (green (543 nm)), $Y_2O_3IEu(III)$ (red (611 nm)), $Mg_4(F)GeO_6IMn$ ((red (658 nm)), $Mg_4(F)(Ge_1Sn)O_6IMn$ (red (658 nm)), $MgWO_4$ (pale blue (473 nm)), $CaWO_4$ (blue (417 nm)), $CaWO_4IPb$ (scheelite, blue (433 nm)), $(Ba_1Ti)_2P_2O_7Ti$ (blue-green (494 nm)), $Sr_2P_2O_7ISn$, blue (460 nm), $Ca_5F(PO_4)_3$:Sb (blue (482 nm)), $Sr_5F(PO_4)_3$:Sb,Mn (blue-green (509 nm)), $BaMgAI_{10}O_{17}IEu_1Mn$ (blue (450 nm)), $BaMg_2AI_{16}O_{27}IEu(II)$ (blue (452 nm)), $BaMg_2AI_{16}O_{27}IEu(II)_1Mn(II)$ (blue (450+515 nm)), $Sr_5CI(PO_4)_3$:Eu(ll) (blue (447 nm)), $Sr_6P_5BO_{20}IEu$ (blue-green (480 nm)), $(Ca_1Zn_1Mg)_3(PO_4J_2ISn$ (orange-pink (610 nm)), $(Sr,Mg)_3(PO_4)_2$:Sn (orange-pinkish white (626 nm)), $CaSiO_3Pb_1Mn$ (orange-pink (615 nm),) $Ca_5F(PO_4)_3$:Sb,Mn (yellow), $Ca_5(F,CI)(PO_4)_3$: Sb,Mn (warm white to cool white or blue or daylight), $(Ca_1Sr_1Ba)_3(PO_4J_2CI_2IEu$ (blue (452 nm)), 3 $Sr_3(PO_4)_2.SrF_2$:Sb,Mn (blue (502 nm)), $Y(P,V)O_4$:Eu (orange-red (619 nm)), $(Zn,Sr)_3(PO_4)_2$:Mn (orange-red (625 nm)), Y_2O_2SiEu (red (626 nm)), $(Sr_1Mg)_3(PO_4)_Z$iSn(II) (orange-red (630 nm)), 3.5 MgO.0.5 $MgF_2.GeO_2$:Mn (red (655 nm)), $Mg_5As_2O_{11})$Mn (red (660 nm)), $Ca_3(PO_4)_2.CaF_2$:Ce,Mn, (yellow (568 nm)), $SrAI_2O_7Pb$ (ultraviolet (313 nm)), $BaSi_2O_5)$Pb (ultraviolet (355 nm)) $SrFB_2O_3$:Eu(ll) (ultraviolet (366 nm)), SrB_4O_7:Eu (ultraviolet (368 nm)), $MgGa_2O_4)$Mn(II), (blue-green), $(Ce_1Tb)MgAI_{11}O_{19}$ (green), Gd_2O_2SiTb (P43) (green (peak at 545 nm)), Gd_2O_2SiEu (red (627 nm)), Gd_2O_2SiPr (green (513 nm)), $Gd_2O_2SiPr_1Ce_1F$ (green (513 nm)), Y_2O_2SiTb (P45) (white (545 nm)), Y_2O_2SiTb (P22R) (red (627 nm)), Y_2O_2SiTb (white (513 nm)), Zn(0.5)Cd(0.4)S:Ag (HS) (green (560 nm)), Zn(0.4)Cd(0.6)S:Ag (HSr) (red (630 nm)), $CdWO_4$ (blue (475 nm)), $CaWO_4$ (blue (410 nm)), $MgWO_4$ (white (500 nm)), Y_2SiO_5ICe (P47) (blue (400 nm)), $YAI0_3$:Ce (YAP) (blue (370 nm)), $Y_3AI_5O_{12}ICe$ (YAG) (green (550 nm)), $Y_3(AI_1Ga)_5O_{12}ICe$ (YGG) (green (530 nm)), CdSiIn (green (525 nm)), ZnOiGa (blue (390 nm)), ZnOiZn (P15) (blue (495 nm)), $(Zn_1Cd)SiCu_1AI$ (P22G) (green (565 nm)), $ZnSiCu_1AI_1Au$ (P22G) (green (540 nm)) ZnCdSiAg, Cu (P20) (green (530 nm)), ZnSiAg (P11) (blue (455 nm)), anthracene (blue (447 nm)), plastic (EJ-212, blue (400 nm)), Zn_2SiO_4IMn (P1) (green (530 nm)), ZnSiCu (GS) (green (520 nm)), CsIiTI (green (545 nm)), $^6LiF/ZnS$: Ag (ND) (blue (455 nm)), and $^6LiF/ZnS$:Cu,AI,Au (NDg) (green (565 nm)),

wherein color of light emitted from each phosphor is listed in parenthesis after the phosphor.

4. LED module lighting system according to claim **2**, wherein:

at least one LED in a MIO-LED device emits blue light; and

phosphor material is yttrium-aluminum-garnet (YAG) phosphor.

5. LED module lighting system according to claim **1**, wherein said DSP is configured to control the power applied to each LED or set of LEDs, such that the colour and brightness of light emitted is the same for each MIO-LED device.

6. LED module lighting system according to claim **1**, further comprising a pulse width modulator (PWM) switch for controlling the power applied to each LED or a set of LEDs, using signals from the DSP.

7. LED module lighting system according to claim **6**, wherein the DSP is configured to control the PWM switch to adjust the power supplied to two or more LEDs of the same colour present in separate MIO-LED devices, when said two or more LEDs emit different shades of said colour.

8. An LED module lighting system according to claim **1**, wherein the DSP is configured to control the DAC to adjust the power supplied to two or more LEDs of the same colour present in separate MIO-LED devices, when said two or more LEDs emit different shades of said colour.

9. An LED module lighting system according to claim **8**, wherein said two or more LEDs of the same colour have not been grouped by binning.

10. LED module lighting system according to claim **1**, further comprising one or more temperature sensors configured to provide temperature information of the module lighting system to the DSP.

11. LED module lighting system according to claim **10**, wherein the DSP is configured to control of the power applied to each LED or set of LEDs of an MIO-LED device based on temperature information received from the temperature sensors, such that the colour and brightness of light emitted from each MIO-LED device is maintained where there are changes in temperature.

12. LED module lighting system according to claim **1**, further comprising one or more air cooling fan, configured to cool at least some of the LEDs.

13. LED module lighting system according to claim **12**, wherein said DSP is configured to control power to the fan based on temperature information received from the temperature sensors.

14. LED module lighting system according to claim **13**, wherein the DSP is configured, such that the colour and brightness of light emitted from each MIO-LED device is maintained where there are changes in temperature.

15. LED module lighting system according to claim **1**, further comprising one or more network interfaces configured to signals to the DSP, allowing an external control.

16. LED module lighting system according to claim **1**, further comprising one or more IR sensors configured provide to signals to the DSP, allowing an external control.

17. LED module lighting system according to claim **1**, further comprising a power supply configured to supply power to the LEDs and other components.

18. LED module lighting system according to claim **17**, wherein said power supply has a plurality of DC voltage outputs, each providing a different voltage to match the rating voltage for a colour-emitting LED.

19. LED module lighting system according to claim **17**, wherein said power supply is configured to adapt output level, for at least one colour dependent, on the required light output, controlled by the DSP.

20. LED module lighting system according to claim **17**, further comprising a secondary induction coupler, which provides power to the power supply by electromagnetic induction from a primary induction coupler.

21. LED module lighting system according to claim **1**, further comprising a memory storage device configured to provide data to the DSP regarding colour and/or brightness compensation information of each MIO-LED device.

22. LED module lighting system according to claim **1**, wherein the DSP is configured to continuously monitor the power supplied to each LED in order to maintain the colour and brightness provided by each MIO-LED device.

23. LED module lighting system according to claim **22**, wherein the colour and brightness are maintained according to relationships between current and colour behavior, and/or light output vs. temperature data.

24. LED module lighting system according to claim **23**, wherein said relationships are stored as data within storage device where present.

25. LED module lighting system according to claim **1**, wherein the colour temperature, CT, of the emitted light is adjustable.

26. LED module lighting system according to claim **1**, capable of emitting light that provides a high colour rendition index, CRI.

27. Modular LED device comprising a housing and one or more LED module systems according to claim **1**, whereby:

an array of MIO-LED devices is arranged as a light emitting surface, and

a mechanical means to stack two or more modular LED devices is provided.

28. Modular LED device according to claim **27**, whereby said mechanical stacking means aligns the respective light emitting surfaces to project light towards the same direction.

29. Modular LED device according to claim **28**, wherein the housing comprises an interfacing material which can be used to make contact with other heat conductive materials, so as to transfer heat from the device more easily.

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