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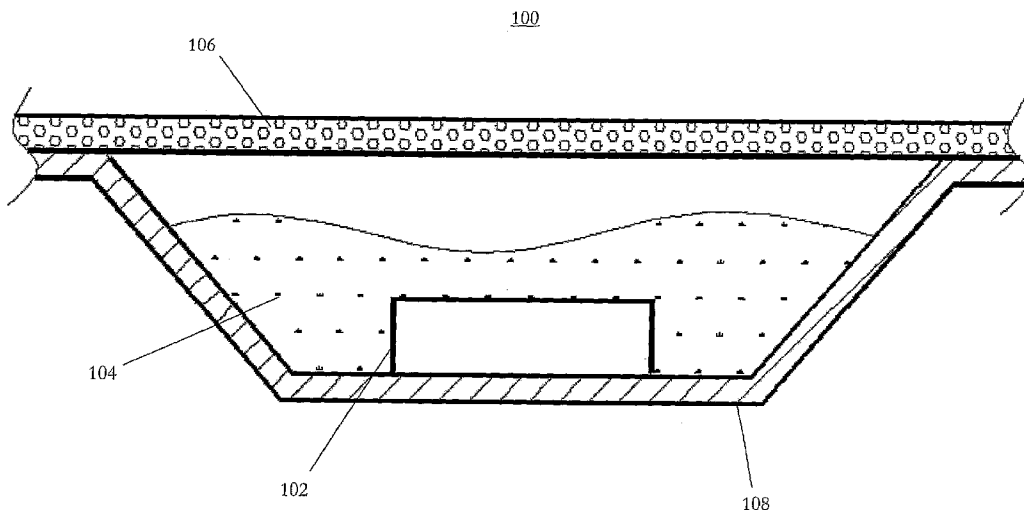
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(54) Title: PACKAGE DESIGN FOR PRODUCING WHITE LIGHT WITH SHORT-WAVELENGTH LEDS AND DOWN-CONVERSION MATERIALS



(57) Abstract: A broad bandwidth light source including: a solid state light emitting device (102) that generates short wavelength light; and quantum dot material (104) and phosphor material (106) that are each irradiated by some of the short wavelength light. The short wavelength light has a spectrum with a first peak wavelength shorter than about 500nm. The quantum dot material (104) absorbs some of the short wavelength light and reemits it as long wavelength light having a spectrum with a second peak wavelength longer than about 600nm. The phosphor material (106) absorbs some of the short wavelength light and reemits it as mid wavelength light having a spectrum with a peak wavelength between the first and second peak wavelengths. The light source is configured such that some of each light (short, mid, and long wavelength) is emitted coincidentally as a light having a chromaticity value near the blackbody locus and a color rendering index greater than 80.

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PACKAGE DESIGN FOR PRODUCING WHITE LIGHT WITH SHORT-WAVELENGTH LEDS AND
DOWN-CONVERSION MATERIALS

RELATED APPLICATION

This application claims the benefit of priority to U.S. Provisional
Application Serial Number 60/693,170, filed June 23, 2005 and to U.S. Provisional
Application No. 60/698,591 filed July 12, 2005, the contents of each being incorporated
by reference herein.

FIELD OF THE INVENTION

[0001] The present invention concerns solid-state white light emitting devices.
In particular, these devices and methods use a short wavelength light source with both
phosphor and quantum dot down conversion materials.

BACKGROUND OF THE INVENTION

[0002] Solid state light emitting devices, including solid state lamps having light
emitting diodes (LED's) and resonant cavity LED's (RCLED's) are extremely useful,
because they potentially offer lower fabrication costs and long term durability benefits
over conventional incandescent and fluorescent lamps. Due to their long operation
(burn) time and low power consumption, solid state light emitting devices frequently
provide a functional cost benefit, even when their initial cost is greater than that of
conventional lamps. Because large scale semiconductor manufacturing techniques may
be used, many solid state lamps may be produced at extremely low cost.

[0003] In addition to applications such as indicator lights on home and consumer
appliances, audiovisual equipment, telecommunication devices and automotive
instrument markings, LED's have found considerable application in indoor and outdoor
informational displays.

[0004] With the development of efficient LED's that emit blue or ultraviolet (UV)
light, it became feasible to produce LED's that generate white light through phosphor
conversion of a portion of the primary emission of the LED to longer wavelengths.
Conversion of primary emissions of the LED to longer wavelengths is commonly
referred to as down-conversion of the primary emission. An unconverted portion of the
primary emission combines with the light of longer wavelength to produce light that
may appear white to a viewer. However, using only inorganic phosphors to down-
convert short wavelength light, the types of spectra that may be produced efficiently
are limited.

SUMMARY OF THE INVENTION

[0005] An exemplary embodiment of the present invention is a method of producing visible light using a short wavelength solid state light emitting device, a quantum dot material and a phosphor material, where the visible light has a chromaticity value near the blackbody locus and a color rendering index greater than about 80. Short wavelength light having a first spectrum with a first peak wavelength is generated using the short wavelength solid state light emitting device. The first peak wavelength is shorter than about 500nm. The quantum dot material is irradiated with at least a portion of the short wavelength light such that a first fraction of the short wavelength light is absorbed and reemitted by the quantum dot material as long wavelength light having a second spectrum with a second peak wavelength. The second peak wavelength is longer than about 600nm. The phosphor material is irradiated with at least a portion of the short wavelength light such that a second fraction of the short wavelength light is absorbed and reemitted by the phosphor material as mid wavelength light having a third spectrum with a third peak wavelength. The third peak wavelength is between the first peak wavelength and the second peak wavelength. A third fraction of the short wavelength light, at least a portion of the mid wavelength light and at least a portion of the long wavelength light are emitted as the visible light.

[0006] Another exemplary embodiment of the present invention is a broad bandwidth light source including: a short wavelength solid state light emitting device; a quantum dot material optically coupled to the short wavelength solid state light emitting device to be irradiated by a first portion of the short wavelength light; and a phosphor material optically coupled to the short wavelength solid state light emitting device to be irradiated by a second portion of the short wavelength light. The short wavelength solid state light emitting device generates short wavelength light having a first spectrum with a first peak wavelength that is shorter than about 500nm. The quantum dot material is adapted to absorb a fraction of incident light having the first spectrum and reemit it as long wavelength light having a second spectrum with a second peak wavelength that is longer than about 600nm. The phosphor material is adapted to absorb a fraction of incident light having the first spectrum and reemit it as mid wavelength light having a third spectrum with a peak wavelength that is between the first peak wavelength and the second peak wavelength. The short wavelength solid state light emitting device, the quantum dot material, and the phosphor material are configured such that some of the short wavelength light, some of the long wavelength light, and some of the mid wavelength light are emitted substantially coincidentally from

the broad bandwidth light source as a visible light having a chromaticity value near the blackbody locus and a color rendering index greater than 80.

[0007] A further exemplary embodiment of the present invention is a broad bandwidth light source for producing visible light having a chromaticity value near a blackbody locus and a color rendering index greater than about 80. The broad bandwidth light source includes: means for generating short wavelength light having a first spectrum with a first peak wavelength; means for absorbing and reemitting a first fraction of the short wavelength light as long wavelength light having a second spectrum with a second peak wavelength; and means for absorbing and reemitting a second fraction of the short wavelength light as mid wavelength light having a third spectrum with a third peak wavelength. The first peak wavelength is shorter than about 500nm, the second peak wavelength is longer than about 600nm, and the third peak wavelength is between the first peak wavelength and the second peak wavelength. A third fraction of the short wavelength light, at least a portion of the mid wavelength light, and at least a portion of the long wavelength light are emitted as the visible light.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The invention is best understood from the following detailed description when read in connection with the accompanying drawings. It is emphasized that, according to common practice, the various features of the drawings are not to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawing are the following figures:

[0009] Figure 1 is a cut away side plan drawing illustrating an exemplary broad bandwidth light source according to an exemplary embodiment of the present invention;

[0010] Figure 2 is a graph illustrating exemplary spectra of a blue light emitting diode, a yellow/green phosphor material, and a red quantum dot (QD) material;

[0011] Figure 3A is a graph illustrating the spectrum of an exemplary broad bandwidth light source according to an exemplary embodiment of the present invention;

[0012] Figure 3B is a CIE-1931 diagram illustrating the color characteristics of an exemplary broad bandwidth light source according to an exemplary embodiment of the present invention;

[0013] Figure 4 is a cut away side plan drawing illustrating another exemplary broad bandwidth light source according to an exemplary embodiment of the present invention;

[0014] Figure 5 is a cut away side plan drawing illustrating a further exemplary broad bandwidth light source according to an exemplary embodiment of the present invention;

[0015] Figure 6 is a flowchart illustrating an exemplary method of producing visible light having a chromaticity value near a blackbody locus and a color rendering index greater than about 80 according to an exemplary embodiment of the present invention;

[0016] Figures 7A and 7B are schematic block diagrams illustrating exemplary methods of producing visible light using a short wavelength solid state light emitting device, a QD material, and a phosphor material according to an exemplary embodiment of the present invention; and

[0017] Figure 7C is a schematic block diagram illustrating an exemplary method of producing visible light using a short wavelength solid state light emitting device and a combined QD/phosphor material according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] Research into solid-state lighting aims not only to develop energy efficient light sources, but also light sources capable of emitting white light that mimics a sunlight spectrum. However, it has been difficult to achieve this type of spectrum efficiently using only inorganic phosphors to down-convert short wavelength light. For example, white LED's using a cerium doped yttrium aluminum garnet (YAG:Ce) phosphor with a gallium nitride (GaN) based blue LED have been produced. In these prior art light sources, a portion of the blue radiation emitted by the GaN LED is down-converted to the green-yellow range by the phosphor. The combined light that results is perceived as white by the human visual system. However, this method has a drawback in that the light produced has a spectrum with a very high correlated color temperature (CCT) and may have poor color rendering properties, especially in the red region. For white LED's to be able to compete with traditional light sources, it is desirable for the spectral power distribution (SPD) to be improved.

[0019] Quantum dots (QD's) are nanometer size semiconductors that have the property of absorbing energy in one spectral range and emitting energy in another spectral range. One of the unique features of QD's that may make them interesting in

solid-state lighting applications is that the absorption and emission spectra of a QD are related to the average physical size of the QD particle. Therefore, by controlling the diameters of the QD's in a material, theoretically, a material that may produce a tailored, continuous emission spectrum from a narrow bandwidth source may be achieved.

[0020] Cadmium selenide-based (CdSe) QD's can be tuned to emit radiation across the entire visible spectrum range (380nm to 780 nm). Therefore, it is contemplated that CdSe-based QD's are a potential down-conversion material for use in white LED applications. Because the peak wavelength of the emission spectrum of QD's is proportional to their average diameters, it may be possible to combine QD's of different diameters to produce an almost continuous spectrum white light when excited by an ultraviolet or blue LED.

[0021] The inventors have tested solid state lighting devices in which red CdSe quantum dots (QD's) (620nm) have been layered around a blue GaN LED. These tests produced a light source with an output color that is purplish blue and a low luminous efficacy. These results are caused by the lack of output energy by these devices in the green-yellow spectral region.

[0022] For general illumination applications, it is almost always desirable to have a light source with a chromaticity near the blackbody locus. The chromaticity of these experimental solid state lighting devices may be improved by adding a certain amount of green QD's to the package. However, it has been found that green QD's have low quantum yields and high self-absorption ratios. Thus, adding green QD's to these experimental light sources may move the chromaticity value of the output light close to the blackbody locus, but the associated quantum yields and self-absorption ratios may greatly decrease package efficiency.

[0023] Exemplary embodiments of the present invention include devices and methods to produce white light that may mimic sunlight using light emitting diodes (LED's) and down-conversion materials. These exemplary embodiments use high efficiency red QD's and yellow-green phosphor as down-conversion materials. Hence, the package luminous efficacy may be increased while maintaining the desired chromaticity value.

[0024] Figure 1 illustrates exemplary broad bandwidth light source 100 according to an exemplary embodiment of the present invention. Exemplary broad bandwidth light source 100 includes: short wavelength solid state light emitting device 102 to generate short wavelength light; QD material 104; and phosphor material 106,

all of which are mounted on optical mount 108. Optical mount 108 provides mechanical support and may also act as a heat sink to help dissipate heat generated by the short wavelength solid state light emitting device 102 and the down-conversion materials. Optical mount 108 may also have a reflective coating to increase emission of the visible light out of the top surface of exemplary broad bandwidth light source 100. It is noted that, although the positions of QD material 104 and phosphor material 106 shown in Figure 1 may be desirable, other configurations of these two material layers may be used in exemplary embodiments of the present invention. For example, the positions of QD material 104 and phosphor material 106 may be exchanged in the exemplary embodiment of Figure 1.

[0025] Exemplary broad bandwidth light source 100 addresses the lack of green-yellow light in the spectrum of the experimental solid state light source described above by creating a packaging concept that couples both red QD's and yellow-green phosphor as down-conversion materials with a solid state blue or UV light source. As shown in Figure 1, short wavelength solid state light emitting device 102 may be embedded within QD material 104 and phosphor material 106 may be layered on top the QD material layer.

[0026] Figures 7A-C schematically illustrate operation of exemplary broad bandwidth light sources. For simplicity of illustration all photons (arrows) are shown propagating forward. One skilled in the art will understand, however, that down-converted photons may be radiated in all directions and the photons of short wavelength solid state light emitting device 102 may not be collimated as shown in Figures 7A-C. In Figures 7A-C, short wavelength photons are represented by arrows marked B, mid wavelength photons are represented by arrows marked G and long wavelength photons are represented by arrows marked R. In all three Figures, photons 700 represent the short wavelength photons generated by short wavelength solid state light emitting device 102.

[0027] In the exemplary embodiment of Figure 7A, photons 700 are incident on phosphor material 106 and some of them are absorbed by phosphor material 106 and reemitted as mid wavelength photons. Photons 702 include non-absorbed, short wavelength photons (B) that are transmitted through phosphor material 106 and emitted mid wavelength photons (G). Photons 702 are incident on QD material 104. Some of remaining short wavelength photons and some of the mid wavelength photons are absorbed by QD material 104 and reemitted as long wavelength photons. The remaining short wavelength photons and the remaining mid wavelength photons (G)

are transmitted through phosphor material 106 and combine with the emitted long wavelength photons (R) to produce broad bandwidth light 704.

[0028] In the exemplary embodiment of Figure 7B, photons 700 are incident on QD material 104 and some of them are absorbed by QD material 104 and reemitted as long wavelength photons. The remaining short wavelength photons are transmitted through QD material 104. Photons 706 include non-absorbed, short wavelength photons (B) that are transmitted through QD material 104 and emitted long wavelength photons (R). Photons 706 are incident on phosphor material 106. Some of remaining short wavelength photons are absorbed by phosphor material 106 and reemitted as mid wavelength photons. The remaining short wavelength photons (B) and the long wavelength photons (R) are transmitted through phosphor material 106 and combine with the emitted mid wavelength photons (G) to produce broad bandwidth light 704.

[0029] In the exemplary embodiment of Figure 7C, photons 700 are incident on combined QD/phosphor material 402 and some of them are absorbed by combined QD/phosphor material 402 and reemitted as mid wavelength photons and long wavelength photons. The remaining short wavelength photons (B) are transmitted through combined QD/phosphor material 402 and combine with the emitted mid wavelength photons (G) and the long wavelength photons (R) to produce broad bandwidth light 704.

[0030] Thus, in all three illustrated embodiments, part of the short wavelength light from short wavelength solid state light emitting device 102 is absorbed by both the QD's in QD material 104 and the phosphor in phosphor material 106 (or in combined QD/phosphor material 402), which absorb the short wavelength light and reemit (i.e. down-convert) it as red and green-yellow light, respectively. Therefore, exemplary broad bandwidth light source 100 may produce an almost continuous spectrum of visible light. As a result, both the chromaticity value and luminous efficacy of exemplary broad bandwidth light source 100 may be improved.

[0031] Other benefits of this broad bandwidth light source design may include: increasing the color rendering index (CRI) of the output light; lowering the correlated color temperature (CCT) of the output light; and increasing the efficiency of the device.

[0032] Figure 2 illustrates spectral graph 200, which includes three spectra. Spectrum 202 represents the spectrum of the short wavelength light generated by an exemplary short wavelength solid state light emitting device 102. Spectrum 204 represents the spectrum of the mid wavelength light emitted by an exemplary phosphor material 106. Spectrum 206 represents the spectrum of the long wavelength light

emitted by an exemplary QD material 104. By properly configuring short wavelength solid state light emitting device 102, QD material 104, and phosphor material 106, the relative amounts of light from each of these spectra may be controlled to produce a visible light with desired optical properties such as chromaticity, CRI, and CCT.

5 Spectral graph 300 in Figure 3A illustrates exemplary combined spectrum 302 that may be produced in this manner.

[0033] By varying the relative contributions of spectrum 202, spectrum 204, and spectrum 206 to the visible light emitted by exemplary broad bandwidth light source 100, the chromaticity value of the emitted light may be changed. The chromaticity value of the emitted light may also be changed by choosing a short wavelength solid state light emitting device, a QD material, and/or a phosphor material that have different spectra than those shown in Figure 2. As noted above, a chromaticity near the black body locus has been found to be most natural to people and, thus, preferred for lighting designs. Figure 3B shows CIE-1931 diagram 304 on which spectrum locus 306, black body locus 308, and chromaticity value 310 of exemplary combined spectrum 302 shown in Figure 3A have been plotted. As may be seen in Figure 3B, chromaticity value 310 of exemplary combined spectrum 302 shown in Figure 3A is very near to black body locus 308. Proper selection and configuration of short wavelength solid state light emitting device 102, QD material 104, and phosphor material 106 may allow the chromaticity value of the visible light emitted from broad bandwidth light source 100 to be desirably set within an area bounded by about .01 of the x chromaticity value and about .01 of the y chromaticity value of the blackbody locus on a CIE-1931 diagram.

[0034] CRI is a figure of merit, on a scale of 0 to 100, used by manufacturers of fluorescent, metal halide and other nonincandescent lighting equipment to describe the visual effect of the light on colored surfaces. Natural daylight and any light source approximating a blackbody source (see color temperature) are assigned a CRI of 100. In a daylighting context, the CRI defines the spectral transmissive quality of glasses or other transparent materials. In this case, values of 95 or better are considered acceptable for allowing true color rendering. Typical cool white fluorescent lamps have a CRI of approximately 62. Fluorescent lamps having rare-earth phosphors have achieved CRI's of 80 and above. The CRI of a typical white LED based on a blue LED and YAG phosphor is between 70 and 78. Proper selection and configuration of short wavelength solid state light emitting device 102, QD material 104, and phosphor material 106 may allow the CRI of the visible light emitted from broad bandwidth light

source 100 to be desirably set to be greater than about 85 or even greater than about 90.

[0035] Short wavelength solid state light emitting device 102 generates short wavelength light that desirably has a peak wavelength shorter than about 500nm, for example between about 200nm and about 500nm.

[0036] The solid state light emitting device may be a light emitting diode (LED), a resonant cavity LED, or a diode laser. Examples of materials from which these devices may be formed include: InGaN; GaN; SiC; GaN on a SiC, and other semiconductor materials.

[0037] QD material 104 is optically coupled to short wavelength solid state light emitting device 102 so that it may be irradiated by a portion of the short wavelength light. In Figure 1, QD material 104 is shown to surround short wavelength solid state light emitting device 102. One skilled in the art will understand that this is not necessary, however, as long as QD material 104 is sufficiently irradiated with the short wavelength light. Providing space between QD material 104 and short wavelength solid state light emitting device 102 may be desirable to reduce optical coupling of short wavelength light emitted by QD material 104 into short wavelength solid state light emitting device 102. Such 'back coupling' of longer wavelength light may lead to undesirable heating of short wavelength solid state light emitting device 102.

[0038] QD material 104 is adapted to absorb a fraction of incident short wavelength light and to reemit the absorbed light as long wavelength light having a peak wavelength that is longer than about 600nm, for example between about 600nm and about 700nm. The full width half maximum (FWHM) of the spectrum of the long wavelength light emitted by QD material 104 may be less than about 50nm, although in some applications a broader spectrum of long wavelength light may be desirable. A broader spectrum of long wavelength light may be particularly desirable if a component of infrared light is to be added to the visible. It is noted that a small contribution of infrared light to visible light has been found to have beneficial psychological and physical effects for some people.

[0039] QD material 104 includes a large number of QD's that are dispersed within a matrix material. This matrix material is desirably substantially transmissive to the visible light being produced by broad bandwidth light source 100. For example, the matrix material may include: UV curable clear resin; thermal curable sol-gel resin; UV curable sol-gel resin; polycarbonate; polystyrene; polymethyl methacrylate (PMMA); polyethylene; various epoxies; silicones; silica; or titania.

[0040] The QD's typically have a diameter in range of about 1.9nm to about 10.0nm, although this range is not limiting, and may be formed of any standard QD material, such as CdSe, ZnS, PbSe, CdTe, PbTe, ZnSe, Si, or Ge, among others.

[0041] Phosphor material 106 is adapted to absorb a fraction of incident short wavelength light and to reemit the absorbed light as a mid wavelength light having a peak wavelength between the peak wavelength of the short wavelength light and the peak wavelength of the long wavelength light, often desirably between about 500nm and about 600nm. The full width half maximum of the spectrum of the mid wavelength light emitted by phosphor material 106 may be less than about 150nm, depending on the specific phosphor used.

[0042] Phosphor material 106 may includes a large number of phosphor particles that are dispersed within a matrix material. As with the matrix material of QD material 104, this matrix material is desirably substantially transmissive to the visible light being produced by broad bandwidth light source 100 and may include, for example: UV curable clear resin; thermal curable sol-gel resin; UV curable sol-gel resin; polycarbonate; polystyrene; polymethyl methacrylate (PMMA); polyethylene; various epoxies; silicones; silica; or titania. Alternatively, phosphor material 106 may be a bulk phosphor material, possibly formed into a flat substrate as shown in Figure 1.

[0043] The phosphor particles or the bulk phosphor material may include at least one standard yellow or green phosphor, such as: ZnS:Cu-Al; ZnSiO₄:Mn²⁺; Sr₃SiO₅:Eu²⁺; BaMgAl₁₀O₁₇:Eu²⁺Mn²⁺; SrAlO₄:Eu,Dy; (YGdCe)₃Al₅O₁₂:Eu; Sr₄Al₁₄O₂₅:Eu; (Ce, Tb)MgAl₁₁O₁₉; or (La, Ce, Tb)PO₄, YAG:Ce, or other phosphors.

[0044] Exemplary broad bandwidth light source 100 illustrated in Figure 1 is configured such that the short wavelength light with which phosphor material 106 is irradiated has first been transmitted through QD material 104 before it is incident on the phosphor material. Although it is contemplated that the positions of QD material 104 and phosphor material 106 may be reversed, the configuration shown in Figure 1 may provide an advantage. As noted above, 'back coupling' of light into short wavelength solid state light emitting device 102 may lead to undesirable heating. If QD material 104 is adapted to absorb and reemit a fraction of the incident mid wavelength light as well as a fraction of the short wavelength light, the configuration shown in Figure 1 may desirably reduce the amount of mid wavelength light that is back coupled into short wavelength solid state light emitting device 102.

[0045] Figures 4 and 5 illustrate alternative exemplary broad bandwidth light sources 400 and 500, respectively. Each of these alternative exemplary broad

bandwidth light sources includes a combined QD/phosphor material. This combined QD/phosphor material includes a plurality of QD's and a plurality of phosphor particles that are dispersed within a matrix material that is substantially transmissive to the visible light of the exemplary broad bandwidth light source. The QD's and the phosphor particles may be dispersed separately in specific regions of the matrix material, or they may be mixedly dispersed within the matrix material.

[0046] Figure 4 illustrates exemplary broad bandwidth light source 400 in which combined QD/phosphor material 402 is formed surrounding short wavelength solid state light emitting device 102. Figure 5 illustrates exemplary broad bandwidth light source 500 in which combined QD/phosphor material 502 is formed on the surface of optical element 504. Optical element 504 may desirably be a light guide that may help to reduce back coupling of mid and long wavelength light from combined QD/phosphor material 502 into short wavelength solid state light emitting device 102.

[0047] An exemplary broad bandwidth light source according to the exemplary embodiment of Figure 1 was formed using a GaN-based bare blue LED device as short wavelength solid state light emitting device 102. This blue LED was immersed in a layer of red QD's that had a peak emission wavelength of 630nm (QD material 104) and a YAG yellow/green phosphor layer (phosphor material 106) was placed in front of the LED and QD material. Measurements of this exemplary device show that the package luminous efficacy was 21lm/W, which is close to that of a corresponding commercially available white LED device which uses a phosphor only down conversion material (23lm/W). However, the exemplary broad bandwidth light source, which produced the exemplary data shown in Figures 3A and 3B, had a CRI of 90 with a chromaticity value close to the blackbody locus. Thus, the inventors were able to demonstrate an exemplary broad bandwidth light source according to an exemplary embodiment of the present invention that achieves superior color quality with a minimal reduction of luminous efficacy.

[0048] Figure 6 illustrates an exemplary method of producing visible light using a short wavelength solid state light emitting device, a QD material, and a phosphor material. The visible light produced by this exemplary method has a chromaticity value near the blackbody locus and a CRI greater than about 80. This method may desirably use any of the exemplary broad bandwidth light sources described above with reference to Figures 1, 4, or 5.

[0049] Short wavelength light is generated using the short wavelength solid state light emitting device, step 600. The short wavelength light has a first spectrum with a peak wavelength that is desirably shorter than about 500nm.

5 **[0050]** The QD material is irradiated with at least a portion of the short wavelength light such that a fraction of the short wavelength light is absorbed and reemitted by the QD material as long wavelength light, step 602. The long wavelength light has a second spectrum with a peak wavelength which is desirably longer than about 600nm.

10 **[0051]** The phosphor material is also irradiated with at least a portion of the short wavelength light such that a fraction of the short wavelength light is absorbed and reemitted by the phosphor material as mid wavelength light, step 604. The mid wavelength light has a third spectrum with a peak wavelength between the peak wavelengths of the short wavelength light and the long wavelength light.

[0052] A remainder of the short wavelength light, at least a portion of the mid wavelength light, and at least a portion of the long wavelength light are emitted from the as exemplary broad bandwidth light source the visible light, step 606.

15 **[0053]** Alternatively, the QD material may be irradiated with at least a portion of the mid wavelength light in addition to the short wavelength light. A fraction of the mid wavelength light may be absorbed and reemitted by the QD material as additional long wavelength light, step 608.

20 **[0054]** Although the invention is illustrated and described herein with reference to specific embodiments, it is not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the invention. In particular, one skilled in the art may understand that many features of the various specifically illustrated embodiments may be mixed to form additional exemplary broad bandwidth light sources and methods also embodied by the present invention.

What is Claimed:

1 1. A method of producing visible light having a chromaticity value
2 near a blackbody locus and a color rendering index greater than about 80, the visible
3 light produced using a short wavelength solid state light emitting device, a quantum
4 dot material and a phosphor material, the method comprising:

5 a) generating short wavelength light having a first spectrum with a
6 first peak wavelength using the short wavelength solid state light emitting device, the
7 first peak wavelength being shorter than about 500nm;

8 b) irradiating the quantum dot material with at least a portion of the
9 short wavelength light such that a first fraction of the short wavelength light is
10 absorbed and reemitted by the quantum dot material as long wavelength light having a
11 second spectrum with a second peak wavelength, the second peak wavelength being
12 longer than about 600nm;

13 c) irradiating the phosphor material with at least a portion of the
14 short wavelength light such that a second fraction of the short wavelength light is
15 absorbed and reemitted by the phosphor material as mid wavelength light having a
16 third spectrum with a third peak wavelength, the third peak wavelength being between
17 the first peak wavelength and the second peak wavelength; and

18 d) emitting a third fraction of the short wavelength light, at least a
19 portion of the mid wavelength light, and at least a portion of the long wavelength light
20 as the visible light.

1 2. A method according to claim 1, wherein the chromaticity value of
2 the visible light emitted in step (d) is within an area bounded by about .01 of an x
3 chromaticity value and about .01 of a y chromaticity value of the blackbody locus on a
4 CIE-1931 diagram.

1 3. A method according to claim 1, wherein the color rendering index
2 of the visible light emitted in step (d) is greater than about 85.

1 4. A method according to claim 1, wherein the color rendering index
2 of the visible light emitted in step (d) is greater than about 90.

1 5. A method according to claim 1, wherein the visible light emitted in
2 step (d) has a correlated color temperature less between about 1000K and about
3 16000K.

1 6. A method according to claim 1, wherein the visible light emitted in
2 step (d) has a correlated color temperature between about 3300K and about 3600K.

1 7. A method according to claim 1, wherein the first peak wavelength
2 of the short wavelength light generated in step (a) by the short wavelength solid state
3 light emitting device is between about 200nm and about 500nm.

1 8. A method according to claim 1, wherein the second peak
2 wavelength of the long wavelength light emitted in step (b) by the quantum dot
3 material is between about 600nm and about 700nm.

1 9. A method according to claim 1, wherein a full width half maximum
2 of the second spectrum of the long wavelength light generated in step (b) by the
3 quantum dot material is less than about 50nm.

1 10. A method according to claim 1, wherein step (b) further includes
2 irradiating the quantum dot material with at least a portion of the mid wavelength light
3 such that a fourth fraction of the mid wavelength light is absorbed and reemitted by the
4 quantum dot material as additional long wavelength light.

1 11. A method according to claim 1, wherein the third peak wavelength
2 of the mid wavelength light emitted in step (c) by the phosphor material is between
3 about 500nm and about 600nm.

1 12. A method according to claim 1, wherein a full width half maximum
2 of the third spectrum of the mid wavelength light generated in step (c) by the phosphor
3 material is less than about 150nm.

1 13. A broad bandwidth light source comprising:
2 a short wavelength solid state light emitting device to generate short
3 wavelength light having a first spectrum with a first peak wavelength, the first peak
4 wavelength being shorter than about 500nm;
5 a quantum dot material optically coupled to the short wavelength solid
6 state light emitting device to be irradiated by a first portion of the short wavelength
7 light, the quantum dot material adapted to absorb a first fraction of incident light
8 having the first spectrum and to reemit the absorbed light as long wavelength light
9 having a second spectrum with a second peak wavelength, the second peak wavelength
10 being longer than about 600nm; and
11 a phosphor material optically coupled to the short wavelength solid state
12 light emitting device to be irradiated by a second portion of the short wavelength light,
13 the phosphor material adapted to absorb a second fraction of incident light having the
14 first spectrum and to reemit the absorbed light as mid wavelength light having a third

15 spectrum with a third peak wavelength, the third peak wavelength being between the
16 first peak wavelength and the second peak wavelength,

17 wherein the short wavelength solid state light emitting device, the
18 quantum dot material, and the phosphor material are configured such that a first
19 amount of the short wavelength light, a second amount of the long wavelength light,
20 and a third amount of the mid wavelength light are emitted substantially coincidentally
21 from the broad bandwidth light source as a visible light having a chromaticity value
22 near a blackbody locus and a color rendering index greater than 80.

1 14. A broad bandwidth light source according to claim 13, wherein the
2 short wavelength solid state light emitting device is one of a short wavelength light
3 emitting diode (LED), a short wavelength resonant cavity LED, or a short wavelength
4 diode laser.

1 15. A broad bandwidth light source according to claim 13, wherein the
2 first peak wavelength of the short wavelength light generated by the short wavelength
3 solid state light emitting device is between about 200nm and about 500nm.

1 16. A broad bandwidth light source according to claim 13, wherein a
2 full width half maximum of the first spectrum of the short wavelength light generated
3 by the short wavelength solid state light emitting device is less than about 50nm.

1 17. A broad bandwidth light source according to claim 13, wherein the
2 quantum dot material includes a plurality of quantum dots dispersed within a matrix
3 material that is substantially transmissive to the visible light.

1 18. A broad bandwidth light source according to claim 17, wherein the
2 plurality of quantum dots include at least one of CdSe quantum dots, ZnS quantum
3 dots, CdTe quantum dots, PbTe quantum dots, ZnSe quantum dots, Si quantum dots,
4 Ge quantum dots, or PbSe quantum dots.

1 19. A broad bandwidth light source according to claim 17, wherein the
2 matrix material includes at least one of UV curable clear resin, thermal curable sol-gel
3 resin, UV curable sol-gel resin, polycarbonate, polystyrene, polymethyl methacrylate
4 (PMMA), polyethylene, epoxies, silicones, silica, or titania.

1 20. A broad bandwidth light source according to claim 13, wherein the
2 second peak wavelength of the long wavelength light emitted by the quantum dot
3 material is between about 600nm and about 700nm.

1 21. A broad bandwidth light source according to claim 13, wherein a
2 full width half maximum of the second spectrum of the long wavelength light generated
3 by the quantum dot material is less than about 50nm.

1 22. A broad bandwidth light source according to claim 13, wherein:
2 the quantum dot material is further optically coupled to the phosphor
3 material to be irradiated by a portion of the mid wavelength light; and

4 the quantum dot material is further adapted to absorb a third fraction of
5 incident light having the third spectrum.

1 23. A broad bandwidth light source according to claim 22, wherein the
2 quantum dot material is disposed within the broad bandwidth light source such that the
3 second portion of the short wavelength light with which the phosphor material is
4 irradiated is transmitted through the quantum dot material before being incident on the
5 phosphor material.

1 24. A broad bandwidth light source according to claim 13, wherein the
2 phosphor material includes a plurality of phosphor particles dispersed within a matrix
3 material that is substantially transmissive to the visible light.

1 25. A broad bandwidth light source according to claim 24, wherein the
2 plurality of phosphor particles include at least one of ZnS:Cu-Al; ZnSiO₄:Mn²⁺;
3 Sr₃SiO₅:Eu²⁺; BaMgAl₁₀O₁₇:Eu²⁺Mn²⁺; SrAlO₄:Eu,Dy; (YGdCe)₃Al₅O₁₂:Eu; YAG:Ce;
4 Sr₄Al₁₄O₂₅:Eu; (Ce, Tb)MgAl₁₁O₁₉; YAG:Ce; or (La, Ce, Tb)PO₄.

1 26. A broad bandwidth light source according to claim 24, wherein the
2 matrix material includes at least one of UV curable clear resin, thermal curable sol-gel
3 resin, UV curable sol-gel resin, polycarbonate, polystyrene, polymethyl methacrylate
4 (PMMA), polyethylene, epoxies, silicones, silica, or titania.

1 27. A broad bandwidth light source according to claim 13, wherein the
2 phosphor material includes at least one of bulk ZnS:Cu-Al; bulk ZnSiO₄:Mn²⁺; bulk
3 Sr₃SiO₅:Eu²⁺; bulk BaMgAl₁₀O₁₇:Eu²⁺Mn²⁺; bulk SrAlO₄:Eu,Dy; bulk (YGdCe)₃Al₅O₁₂:Eu;
4 bulk Sr₄Al₁₄O₂₅:Eu; bulk (Ce, Tb)MgAl₁₁O₁₉; or bulk (La, Ce, Tb)PO₄.

1 28. A broad bandwidth light source according to claim 13, wherein the
2 third peak wavelength of the mid wavelength light emitted by the phosphor material is
3 between about 500nm and about 600nm.

1 29. A broad bandwidth light source according to claim 13, wherein a
2 full width half maximum of the third spectrum of the mid wavelength light generated by
3 the phosphor material is less than about 150nm.

1 30. A broad bandwidth light source according to claim 13, wherein:
2 the quantum dot material includes a plurality of quantum dots;
3 the phosphor material includes a plurality of phosphor particles; and
4 the plurality of quantum dots and the plurality of phosphor particles are
5 mixedly dispersed within a matrix material that is substantially transmissive to the
6 visible light.

1 31. A broad bandwidth light source according to claim 13, wherein the
2 short wavelength solid state light emitting device, the quantum dot material, and the
3 phosphor material are configured such that the chromaticity value of the visible light
4 emitted from the broad bandwidth light source is within an area bounded by about .01
5 of an x chromaticity value and about .01 of a y chromaticity value of the blackbody
6 locus on a CIE-1931 diagram.

1 32. A broad bandwidth light source according to claim 13, wherein the
2 short wavelength solid state light emitting device, the quantum dot material, and the
3 phosphor material are configured such that the color rendering index of the visible light
4 emitted from the broad bandwidth light source is greater than about 85.

1 33. A broad bandwidth light source according to claim 2, wherein the
2 short wavelength solid state light emitting device, the quantum dot material, and the
3 phosphor material are configured such that the color rendering index of the visible light
4 emitted from the broad bandwidth light source is greater than about 90.

1 34. A broad bandwidth light source according to claim 13, wherein the
2 short wavelength solid state light emitting device, the quantum dot material, and the
3 phosphor material are configured such that the color rendering index of the visible light
4 emitted from the broad bandwidth light source has a correlated color temperature
5 between about 1000K and about 16000K.

1 35. A broad bandwidth light source according to claim 13, wherein the
2 short wavelength solid state light emitting device, the quantum dot material, and the
3 phosphor material are configured such that the color rendering index of the visible light
4 emitted from the broad bandwidth light source has a correlated color temperature
5 between about 3300K and about 3600K.

1 36. A broad bandwidth light source for producing visible light having a
2 chromaticity value near a blackbody locus and a color rendering index greater than
3 about 80, the broad bandwidth light source comprising:

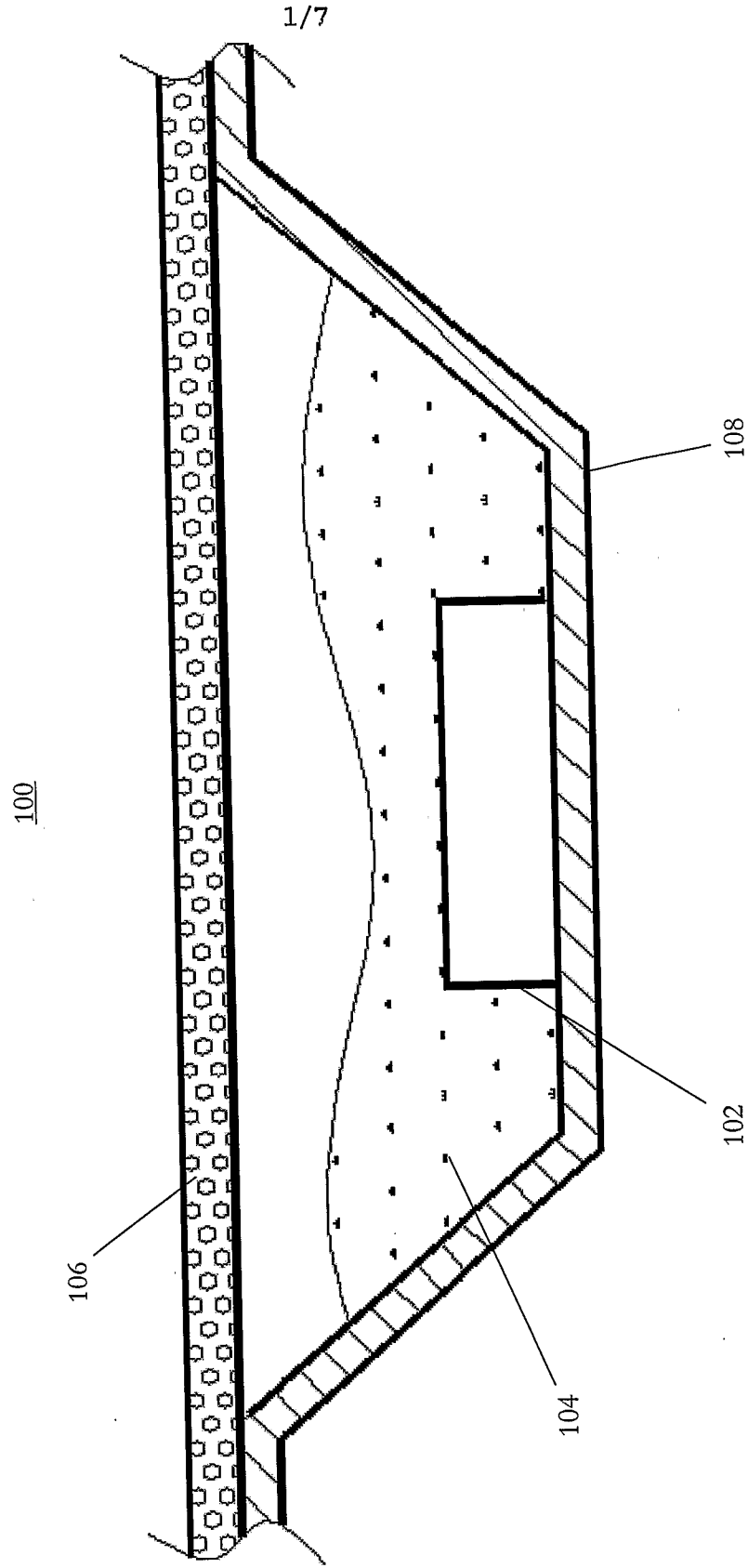
4 means for generating short wavelength light having a first spectrum with
5 a first peak wavelength, the first peak wavelength being shorter than about 500nm;

6 means for absorbing and reemitting a first fraction of the short
7 wavelength light as long wavelength light having a second spectrum with a second
8 peak wavelength, the second peak wavelength being longer than about 600nm; and

9 means for absorbing and reemitting a second fraction of the short
10 wavelength light as mid wavelength light having a third spectrum with a third peak
11 wavelength, the third peak wavelength being between the first peak wavelength and
12 the second peak wavelength,

13 wherein a third fraction of the short wavelength light, at least a portion
14 of the mid wavelength light, and at least a portion of the long wavelength light are
15 emitted as the visible light.

Figure 1



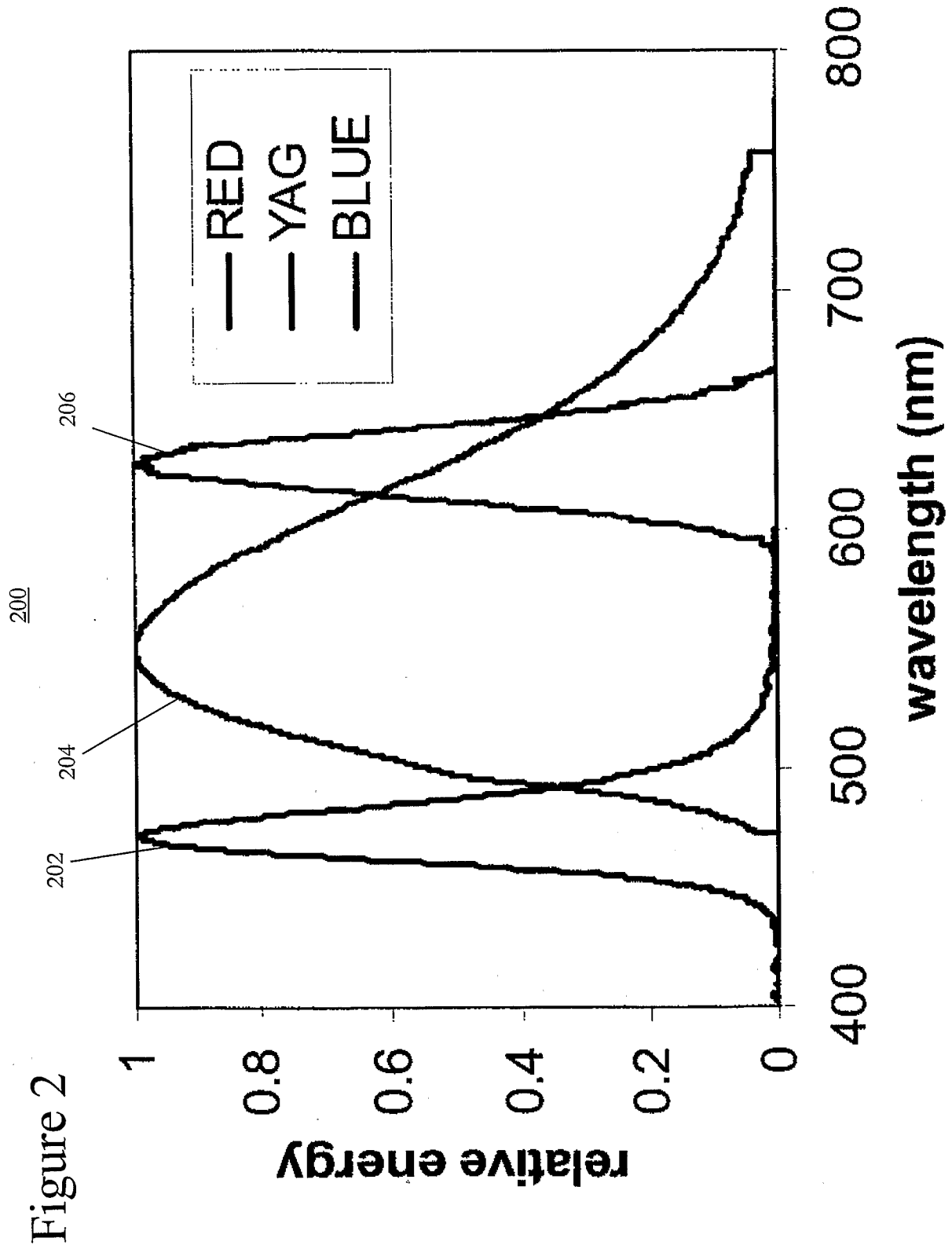


Figure 3B

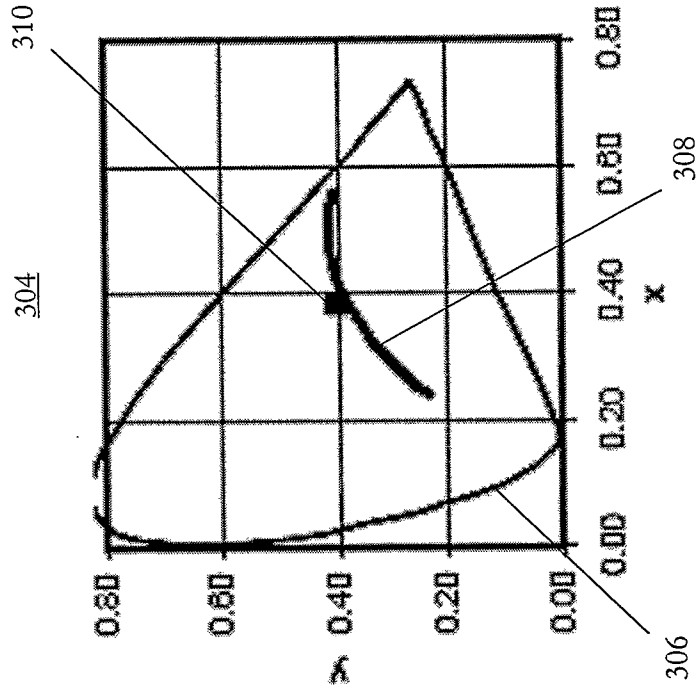


Figure 3A

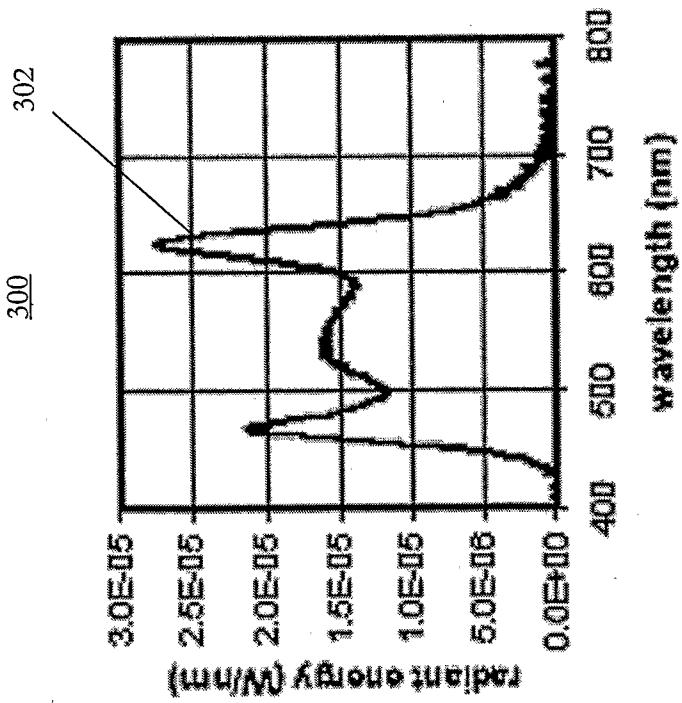


Figure 4

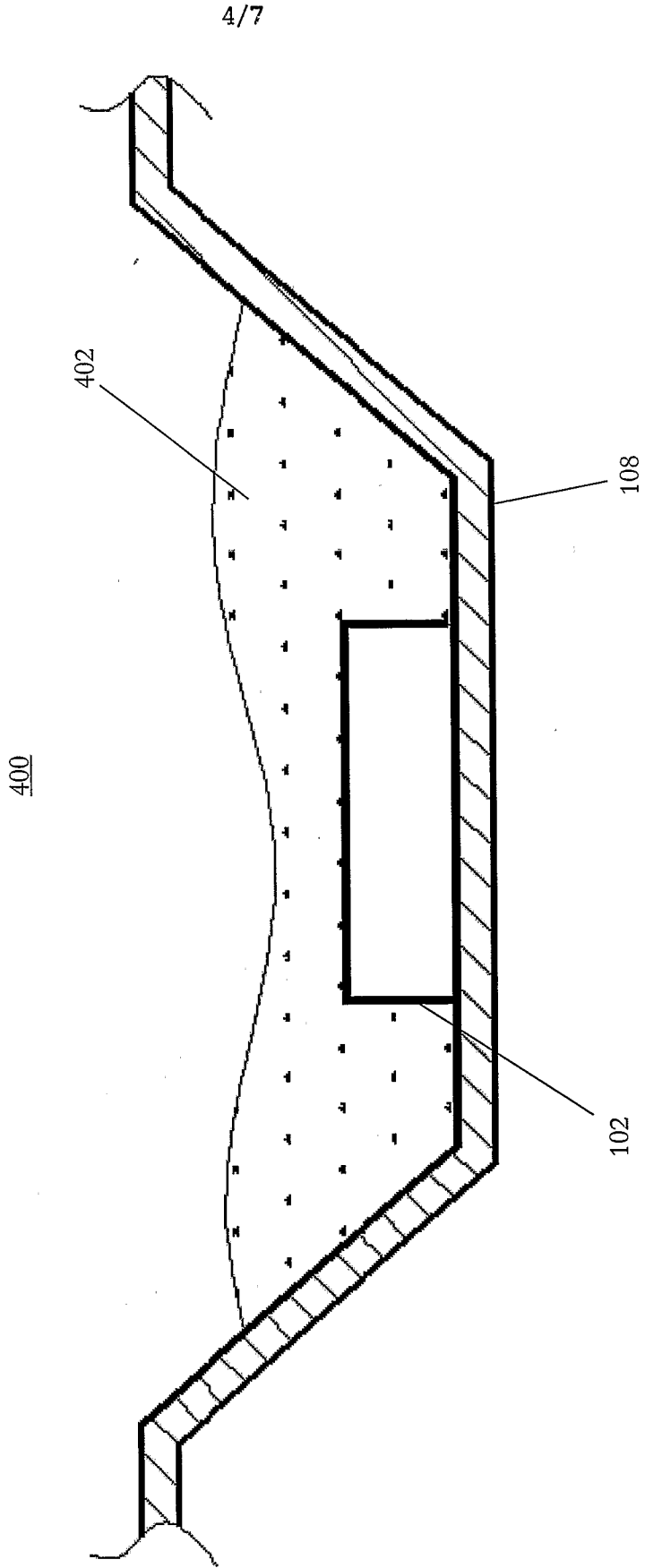


Figure 5

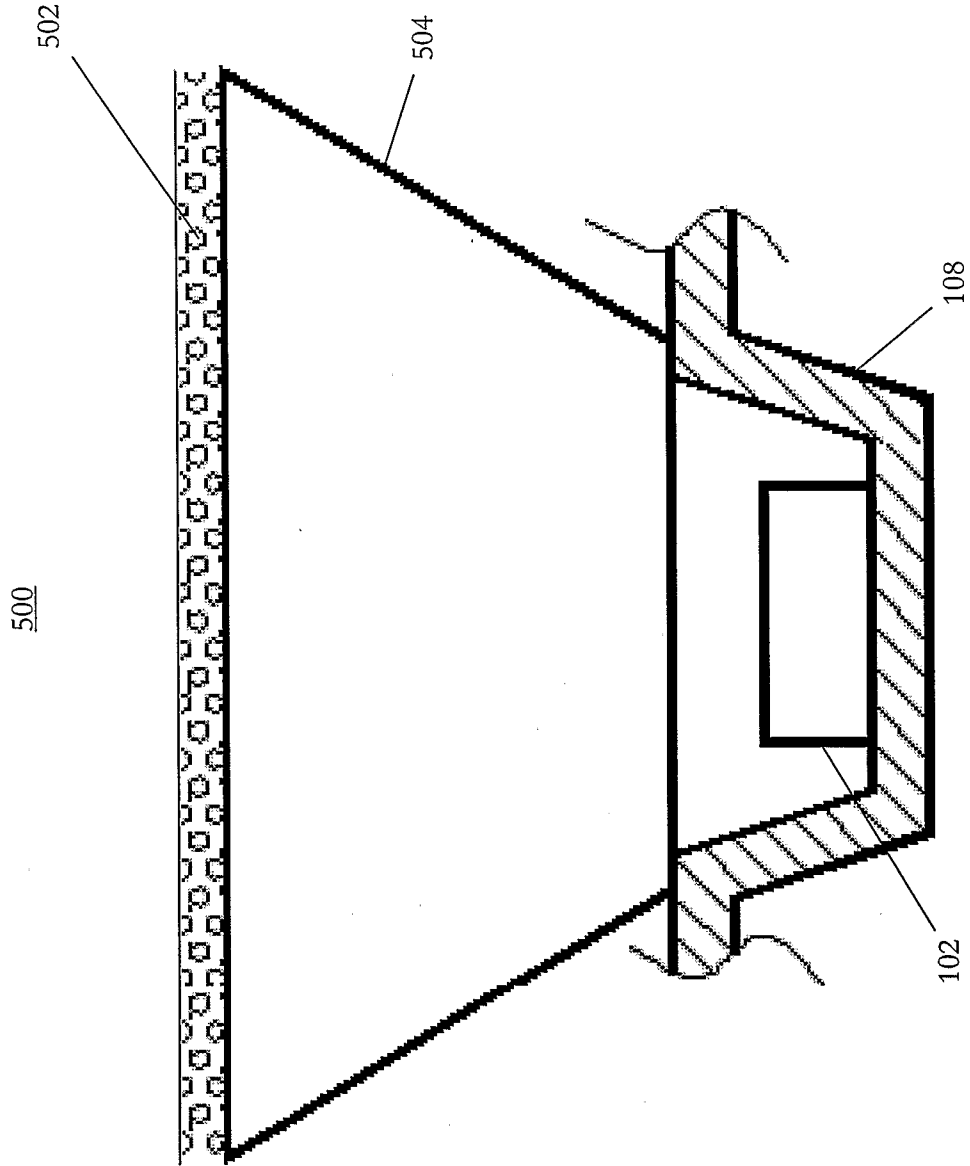


Figure 6

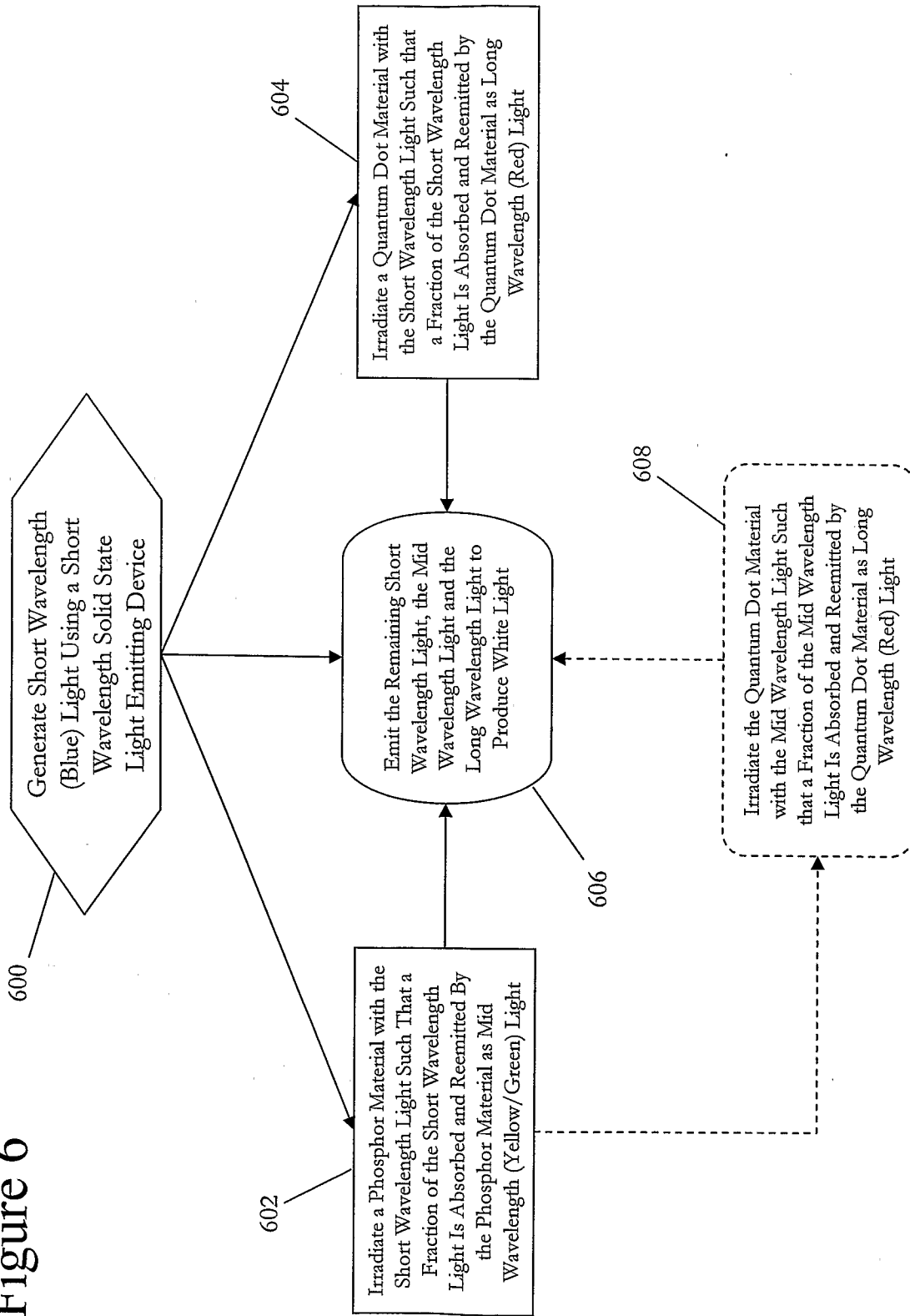


Figure 7B

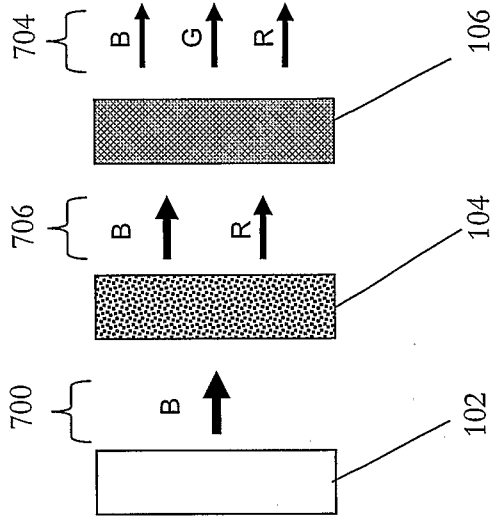


Figure 7A

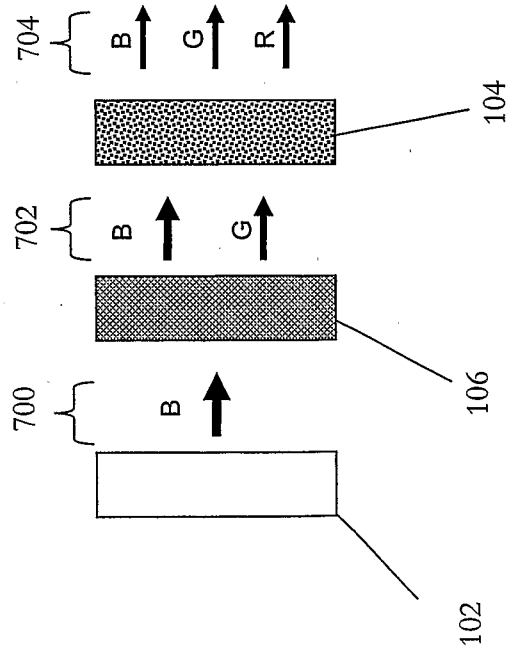
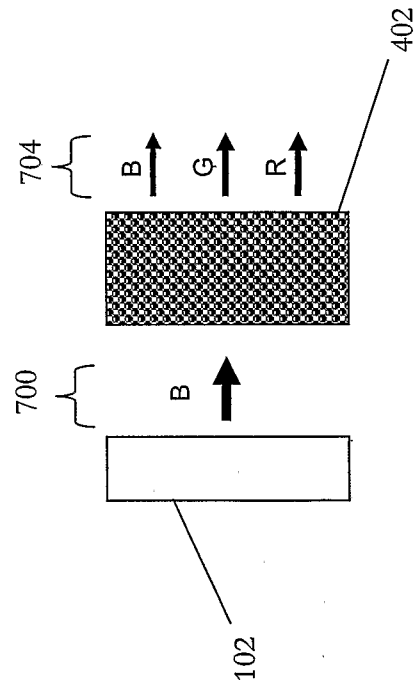


Figure 7C



INTERNATIONAL SEARCH REPORT

International application No

PCT/US2006/024210

A. CLASSIFICATION OF SUBJECT MATTER INV. H01L33/00		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) H01L H01S		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal, INSPEC		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/027062 A1 (SHIANG JOSEPH JOHN [US] ET AL) 12 February 2004 (2004-02-12) paragraph [0045]	1-36
X	EP 1 369 935 A (LUMILEDS LIGHTING US LLC [US]) 10 December 2003 (2003-12-10) paragraphs [0040] - [0043]	1-36
X	US 2003/203524 A1 (FARAHI FARAMARZ [US] ET AL) 30 October 2003 (2003-10-30) paragraph [0008]	1-36
A	US 2004/245912 A1 (THURK PAUL [US] ET AL) 9 December 2004 (2004-12-09) abstract	2-6, 31-36
	----- -/--	
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.		
* Special categories of cited documents :		
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention	
"E" earlier document but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone	
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"P" document published prior to the international filing date but later than the priority date claimed		
Date of the actual completion of the international search	Date of mailing of the international search report	
28 September 2006	12/10/2006	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Jobst, Bernhard	

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/024210

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 102 61 428 A1 (OSRAM OPTO SEMICONDUCTORS GMBH [DE]) 22 July 2004 (2004-07-22) paragraphs [0018] - [0022] -----	23
A	US 2003/127660 A1 (BAWENDI MOUNGI G [US] ET AL) 10 July 2003 (2003-07-10) the whole document -----	1-36
P,X	US 2005/135079 A1 (YIN CHUA JANET B [MY] ET AL) 23 June 2005 (2005-06-23) paragraph [0025] -----	1-36
P,X	US 2006/066210 A1 (NG KEE Y [MY] ET AL) 30 March 2006 (2006-03-30) paragraph [0012] -----	1-36
P,X	US 2006/081862 A1 (CHUA JANET B Y [MY] ET AL CHUA JANET BEE YIN [MY] ET AL) 20 April 2006 (2006-04-20) paragraph [0015] -----	1-36
P,A	HSUEH-SHIH CHEN ET AL: "InGaN-CdSe-ZnSe quantum dots white LEDs" IEEE PHOTONICS TECHNOLOGY LETTERS IEEE USA, vol. 18, no. 1, January 2006 (2006-01), pages 193-195, XP002400867 ISSN: 1041-1135 figures 2,6 -----	1-36

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2006/024210

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 2004027062	A1	12-02-2004	US 2004104672 A1	03-06-2004
EP 1369935	A	10-12-2003	AU 2003232393 A1	22-12-2003
			WO 03105242 A1	18-12-2003
			JP 2004015063 A	15-01-2004
			US 2005215164 A1	29-09-2005
			US 2003227249 A1	11-12-2003
US 2003203524	A1	30-10-2003	US 2003124754 A1	03-07-2003
			US 2003193982 A1	16-10-2003
			US 2003203315 A1	30-10-2003
US 2004245912	A1	09-12-2004	NONE	
DE 10261428	A1	22-07-2004	NONE	
US 2003127660	A1	10-07-2003	EP 1070355 A1	24-01-2001
			JP 2002510866 T	09-04-2002
			WO 9950916 A1	07-10-1999
			US 6501091 B1	31-12-2002
			US 2003127659 A1	10-07-2003
			US 6803719 B1	12-10-2004
US 2005135079	A1	23-06-2005	NONE	
US 2006066210	A1	30-03-2006	CN 1755958 A	05-04-2006
			JP 2006108661 A	20-04-2006
US 2006081862	A1	20-04-2006	CN 1761078 A	19-04-2006
			JP 2006114900 A	27-04-2006