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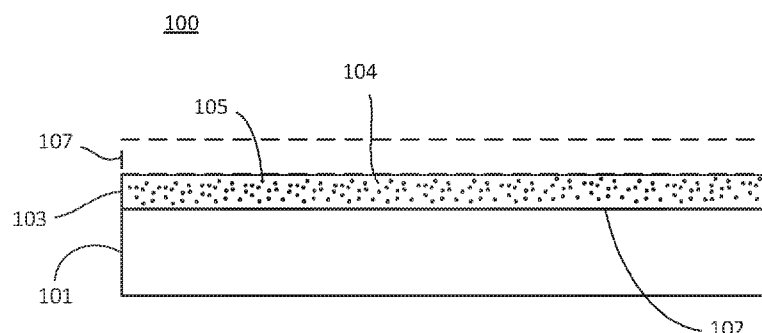


FIG. 1

(57) Abstract: Wavelength converters (103) including a porous matrix layer (104) are described. In some embodiments the porous matrix layer (104) includes pore structures, which are at least partially infiltrated with one or more types of wavelength converting particles (105), such as quantum dot particles. Methods of making such wavelength converters (103) and lighting devices (100) including such wavelength converters (103) are also described.



WAVELENGTH CONVERTERS INCLUDING A POROUS MATRIX, LIGHTING DEVICES INCLUDING THE SAME, AND METHODS OF FORMING THE SAME

CROSS REFERENCE TO RELATED APPLICATION

[0001] The present application is an international application that claims the benefit of and priority to United States Application No. 62/336,274, filed May 13, 2016, which is herein incorporated by reference in its entirety.

FIELD

[0002] The present disclosure generally relates to wavelength converters, methods of making the same, and lighting devices including the same. More particularly, the present disclosure generally relates to wavelength converters that include a porous matrix infiltrated with one or more wavelength conversion materials, methods of making such wavelength converters, and lighting devices including such wavelength converters.

BACKGROUND

[0003] Light emitting diodes (LEDs) can generate visible or non-visible light (hereinafter, “primary light”) in a specific region of the electromagnetic spectrum, e.g., primary light may be emitted in the blue, red, green, ultra-violet (UV), or near-UV regions depending on the material composition of the LED. Wavelength converters may be used to construct an LED light source that produces light having a color different from that of the primary light output from the LED. Generally, the wavelength converter functions to convert all or a portion of primary light output from an LED chip having a first wavelength or wavelength range to light having a second wavelength or wavelength range (hereinafter, “secondary light”).

[0004] Some wavelength converters include a wavelength converting composition that includes a matrix that encapsulates or otherwise supports a wavelength conversion material. In some instances the matrix may be a polymeric material such as a silicone or epoxy polymer, although other materials may be used. Regardless of the composition of the matrix, the wavelength conversion material (e.g., relatively large phosphor particles) generally functions to convert primary light to secondary light, e.g., via photoluminescence. Alternatively, some wavelength converters do not include a matrix. For example, some wavelength converters are in the form of one or more sintered ceramic phosphor plates that may be disposed above and/or around the light emitting surface of an LED.

[0005] Some wavelength converters may include one or more wavelength conversion materials that absorb relatively high energy primary light that is incident thereon. Such absorption may excite the wavelength conversion material to a higher energy state. Subsequently, the wavelength conversion material may return to a lower energy state, at which time it may emit secondary light of a wavelength or wavelength range that is different than the wavelength/wavelength range of the incident primary light. The wavelength/wavelength range of the secondary light may depend on the type of wavelength conversion material used in the wavelength converter. Secondary light of a desired wavelength/wavelength range may therefore be attained by proper selection of wavelength conversion material. An LED that is combined with a wavelength converter to produce secondary light may be understood to be a “wavelength converted LED.”

[0006] Quantum dots (QDs) (also referred to as semiconductor nanocrystals) are relatively new materials that have potential use in the lighting industry. Like conventional phosphor particles, some quantum dots have the ability to absorb incident primary light and to emit secondary light in another portion of the electromagnetic spectrum. Many QDs exhibit properties that can be leveraged to create light converters with precisely designed output spectra. Such properties include, for example, a broad absorption spectrum (freedom of the choice of the pump (primary light) wavelength) and emission of secondary light within a narrow-band (30-50 nm), with the peak emission wavelength determined by the material and size of the QDs. The peak emission wavelength of the QDs may therefore be finely tuned, e.g., within few nanometers, by controlling their size. As a result, QDs may enable lighting designers to create wavelength converters that produce secondary light that includes a finely tuned spectrum of emission colors. Quantum dots have therefore been investigated for potential use in the formation of novel wavelength converters for light-emitting semiconductor devices such as LEDs.

[0007] In many instances wavelength converters such as those noted above are coupled to or in proximity to the emission surface of an LED. For example, many wavelength converters are coupled to the emitting surface of an LED by a thin layer of an adhesive, such as polymer. Although effective in many cases, use of polymeric adhesives may be undesirable for use in high temperature applications and lighting devices that produce a relatively high luminous flux. In such applications, the adhesive may be exposed to temperatures that would cause it to discolor and/or thermally degrade, potentially compromising its optical properties.

[0008] Other mechanisms for bonding a wavelength converter to an emission surface of an LED have also been investigated. For example, research has been performed into the use of a thin layer of low temperature glass to bond a wavelength converter to an emission surface of an LED. Moreover, sophisticated deposition techniques such as pulsed laser deposition (PLD) to form a wavelength converter directly on the emitting surface of an LED. Although such techniques have shown some promise, they may not be suitable for some lighting applications for a variety of reasons. For example, existing methods of forming thin glass layers suitable for bonding a wavelength converter to an LED may be labor intensive, difficult to implement in volume production, and suffer from variability in the thickness of the glass layer. Likewise, PLD methods that deposit a wavelength conversion material require the use of an (expensive) PLD tool. Such methods may therefore not enable a desired level of control over the peak emission wavelength of a wavelength converter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Reference is now made to the following detailed description which should be read in conjunction with the following figures, wherein like numerals represent like parts:

[0010] FIG. 1 illustrates one example of a lighting device including a wavelength converter consistent with the present disclosure;

[0011] FIG. 2 depicts example operations of one example of a method of forming a lighting device including a wavelength converter consistent with the present disclosure.

[0012] FIGS. 3A-3D stepwise illustrate the formation of a lighting device in accordance with a method consistent with the present disclosure.

[0013] FIG. 4 is another example of a lighting device including a wavelength converter consistent with the present disclosure.

DETAILED DESCRIPTION

[0014] The present disclosure will now proceed with reference to the accompanying drawings, in which example embodiments consistent with the present disclosure are shown. It should be understood that the examples in the figures are for the sake of illustration and ease of understanding only and that the methods, wavelength converters, and devices described herein may be embodied in many forms and are not limited to the illustrated embodiments in the FIGS. or specific embodiments described herein.

[0015] One or more elements of the present disclosure may be numerically designated, e.g., as a first, second, third, etc. element. In this context it should be understood

that the numerical designation is for the sake of clarity only (e.g., to distinguish one element from another), and that elements so designated are not limited by their specific numerical designation. Moreover the specification may from time to time refer to a first element may be described as being “on” a second element. In that context it should be understood that the first element may be directly on the second element (i.e., without intervening elements there between), or that one or more intervening elements may be present between the first and second elements. In contrast, the term “directly on” means that the first element is present on the second element without any intervening elements there between.

[0016] As used herein singular expressions such as “a,” “an,” and “the” are not limited to their singular form, and are intended to cover the plural forms as well unless the context clearly indicates otherwise. Specific terms/phrases excepted from this understanding include “single layer,” and “single layer wavelength converter,” which are used herein to designate a single (i.e., one) layer and a wavelength converter that is made up of a single (i.e. one) layer. As will be described in detail below non-limiting examples of single layer wavelength converters consistent with the present disclosure include a single layer of matrix material including wavelength converting particles, such as but not limited to a combination of phosphor particles and quantum dot particles. This is in contrast to multilayer wavelength converters, in which several layers of different wavelength converting compositions are stacked on or otherwise aligned with one another.

[0017] As used herein, the terms “substantially” and “about” when used in connection with an amount or range mean plus or minus 5% of the stated amount or the endpoints of the stated range.

[0018] As used herein, the term “optically transparent” when used in connection with a material (e.g., a matrix or other material) means that the referenced material transmits greater than or equal to about 80% of incident light, such as greater than or equal to about 90%, greater than or equal to about 95%, greater than or equal to about 99%, or even about 100% of incident light. The incident light may be primary and/or secondary light of a specified wavelength or wavelength range (e.g., ultraviolet, visible, infrared, etc.), or may span multiple wavelength ranges. Without limitation, materials described herein as being optically transparent preferably transmit greater than or equal to about 95% (e.g., greater than or equal to about 99% or even about 100%) of primary and/or secondary light in at least one of the ultraviolet, visible, and infrared regions of the electromagnetic spectrum.

[0019] As used herein, the terms, “light emitting diode,” “LED,” and “LED light source” are used interchangeably, and refer to any light emitting diode or other type of

semiconductor-based system that is capable of generating radiation in response to an electrical signal. Thus, the term LED may include, but is not limited to, light-emitting diodes, laser diodes, light emitting polymers, light emitting strips, electro-luminescent strips, combination thereof and the like.

[0020] In particular, the term LED refers to light emitting diodes of all types (including semi-conductor and organic light emitting diodes) that may be configured to generate light in all or various portions of one or more of the visible, ultraviolet, and infrared regions of the electromagnetic spectrum. Non-limiting examples of suitable LEDs that may be used include various types of infrared LEDs, ultraviolet LEDs, red LEDs, green LEDs, blue LEDs, yellow LEDs, amber LEDs, orange LEDs, and white LEDs. (References to the color of a phosphor, LED or conversion material refer generally to its emission color unless otherwise specified. Thus, a blue LED emits a blue light, a yellow phosphor emits a yellow light and so on.) Such LEDs may be configured to emit light over a broad spectrum (e.g., the entire visible light spectrum) or a narrow spectrum.

[0021] As used herein, the term “on” may be used to describe the relative position of one component (e.g., a first layer) relative to another component (e.g., a second layer). In such instances the term “on” should be understood to indicate that a first component is present above a second component, but is not necessarily in contact with one or more surfaces of the second component. That is, when a first component is “on” a second component, one or more intervening components may be present between the first and second components. In contrast, the term “directly on” should be interpreted to mean that a first component is in contact with a surface (e.g., an upper surface) of a second component. Therefore when a first component is “directly on” a second component, it should be understood that the first component is in contact with the second component, and that no intervening components are present between the first and second components.

[0022] From time to time one or more aspects of the present disclosure may be described using ranges. In such instances it should be understood that the indicated ranges are exemplary only unless expressly indicated otherwise. Moreover, the indicated ranges should be understood to include all of the individual values of falling within the indicated range, as though such values were expressly recited. Moreover, the ranges should be understood to encompass sub ranges within the indicated range, as though such sub ranges were expressly recited. By way of example, a range of 1 to 10 should be understood to include 2, 3, 4... etc., as well as the range of 2 to 10, 3 to 10, 2 to 8, etc., as though such values and ranges were expressly recited.

[0023] As briefly described in the background quantum dots (i.e., semiconductor nanocrystals) have been investigated for use in lighting applications, e.g., as a material for converting primary light from a light source (e.g., a light emitting diode) to secondary light. Although research has shown that quantum dots have some promise for use in such applications, new types of wavelength converters including quantum dots and novel methods of manufacturing such converters remain of interest.

[0024] One aspect of the present disclosure therefore relates to wavelength converters that include a porous matrix material and one or more wavelength conversion materials. In various embodiments the porous matrix may be in the form of a (pre-formed) porous layer of one or more matrix materials, wherein the layer includes a multiple open pores, cavities, voids, channels, and the like, which for convenience are individually and collectively referred to herein as a “pore structure” or “pore structures”. In such instances, the pore structures may extend fully or partially through the thickness of the porous matrix or, more particularly, the (pre-formed) layer of porous matrix material. It should therefore be understood that in the context of the present disclosure, the term “pore structure” refers to pores defined by and/or within an otherwise solid body of a matrix material. Without limitation, in some embodiments the porous matrix may include a network of pore structures, i.e., a plurality of pore structures, at least a portion of which are interconnected with one another.

[0025] The wavelength conversion materials described herein may be in the form of particles that are capable of converting incident primary light (e.g., from a light source such as an LED) to secondary light. Without limitation, in some embodiments the wavelength conversion materials are impregnated and/or infiltrated into at least a portion of the pore structures in the porous matrix. For example when the pore structures of the porous matrix include a network of open pores and/channels, the wavelength conversion materials described herein may be present within at least a portion of such open pores/channels. In some embodiments, the wavelength conversion materials described herein are in the form of one or more types of quantum dots, and are embedded, infiltrated, or otherwise disposed within at least a portion of the pore structures present in a porous layer of a matrix material.

[0026] As will be described in detail below, the wavelength converters of the present disclosure may offer a number of advantages that may render them of particular interest for use in a variety of lighting applications, such as in wavelength converted LEDs. For example, the wavelength converters described herein may be produced by a relatively simple process that may lend itself to commercial scale production. The wavelength

converters may also be adhered to (i.e., disposed directly on) a surface of a light source such as an emitting surface of an LED, without the need for an adhesive. Moreover and due at least in part to the properties of the matrix material used to form the porous matrix, the wavelength converters described herein may be advantageously used at relatively high temperatures, which may allow lighting designers to produce lighting devices with increased light output (luminous flux). Finally, in instances where the wavelength converters described herein include quantum dots as a wavelength conversion material, they may enable lighting designers to finely tune the spectrum of (secondary) light emitted by the wavelength converter.

[0027] Consistent with the foregoing discussion, one aspect of the present disclosure relates to wavelength converters, such as but not limited to single layer wavelength converters. In that regard, the wavelength converters described herein generally include a porous layer of a matrix material (also referred to as a “porous matrix” or “porous matrix layer”) that includes one or more pore structures, wherein one or more wavelength conversion materials are present within at least a portion of such pore structures. Without limitation, in some embodiments the wavelength converters of the present disclosure include a pre-formed porous matrix layer that includes pore structures, wherein one or more types of wavelength converting particles have been infiltrated, embedded, impregnated, etc. into such pore structures. In various embodiments, the wavelength converting particles comprise, consist essentially of, or consist of non-agglomerated particles of wavelength conversion material, such as but not limited to non-agglomerated quantum dot particles.

[0028] For convenience and ease of understanding, the present disclosure focuses on embodiments in which the porous matrix is in the form of a substantially flat layer that includes one or more pore structures. It should be understood that such description is for the sake of example only, and that the porous matrix need not be in the form of a substantially flat layer. Indeed the present disclosure envisions the use of porous matrices that have a wide variety of different shapes. For example in some embodiments, the porous matrix may have a curved or lenticular cross section, an irregular cross section, or the like.

[0029] The porous matrices described herein may include or be formed from one or more matrix materials. In that regard any suitable material may be used. Non-limiting examples of materials that may be used to form the porous matrix include various inorganic oxides, nitrides, oxynitrides, combinations thereof, and the like, such as but not limited to zinc oxide (ZnO), alumina (Al₂O₃), aluminum nitride, aluminum oxynitride (AlON), titanium dioxide (TiO₂), zinc sulfide (ZnS), zinc selenide (ZnSe), zirconium dioxide (ZrO₂), silica

(SiO₂) (e.g., vitreous silica), silicates (e.g., soda-lime silicate, sodium borosilicate, lead-alkali silicate, aluminosilicate, etc.), optical glass, garnets (e.g., yttrium aluminum garnet (YAG), lutetium aluminum garnet (LuAG), etc.) combinations thereof, and the like. Of course, such materials are enumerated for the sake of example only, and it should be understood that other materials may be used to form the porous matrix. Without limitation, in some embodiments the wavelength converters described herein include a porous matrix that includes one or more materials that are optically transparent to incident primary light (e.g., from a light source), and/or secondary light (e.g., emitted from one or more wavelength conversion materials) in at least a portion of the ultraviolet, visible, and/or infrared regions of the electromagnetic spectrum.

[0030] As noted above, the wavelength converters described herein may be suitable for use in various lighting applications, including but not limited to high temperature lighting applications. In such instances it may be desirable to form the porous matrix from one or more materials that exhibits a desired level of thermal conductivity, e.g., between greater than 0 to about 40 watts per meter kelvin (W/mK), such as from greater than or equal to about 0.2 to about 40 W/mK, greater than or equal to about 1 to about 40 W/mK, or even from greater than or equal to about 4 to about 30 W/mK. Put in other terms, in some embodiments the porous matrix is formed from a matrix precursor material having a thermal conductivity greater than or equal to about 0.2, 1, 2, 4, 5, 10, or even 15 W/mK. Alternatively or additionally, in some embodiments the porous matrix itself has a thermal conductivity greater than or equal to about 0.2, 1, 2, 4, 5, 10, or even 15 W/mK. With that in mind, Table 1 below identifies example thermal conductivities for films formed from various matrix materials that may be suitably used in the porous matrices described herein.

TABLE 1

Material	Example Thermal Conductivity (W/mK)
Al₂O₃	~12-38.5
SiO₂	~1.4
TiO₂	~4.8-11.8
Yttrium Aluminum Garnet (YAG)	~14
ZnO	~40
ZrO₂	~1.7-2.7

Of course, the materials in Table 1 are listed for the sake of example, and other materials may also be used in the porous matrices of the present disclosure.

[0031] A wide variety of methods may be used to form the porous matrices of the present disclosure. For example and as will be described in greater detail below in connection with FIGS. 2 and 3A-3D, in some embodiments the wavelength converters described herein may include a porous matrix material that is in the form of a layer or other geometric shape. With that in mind, in some instances it may be advantageous to form the layer or other structure of porous matrix material prior to the introduction of wavelength conversion materials (e.g., quantum dots) therein. For convenience, such a material may be referred to herein as a “pre-formed porous matrix layer,” or simply a “pre-formed layer.”

[0032] For example, in some embodiments the porous matrices described herein may be constructed by depositing a layer of matrix precursor material (hereinafter, “matrix precursor”) on a support, and processing the layer of matrix precursor to produce a pre-formed porous matrix layer. A wide variety of supports are suitable for such purposes, such as a substrate, circuit board, an emitting surface of a light emitting diode, etc. Without limitation, in some embodiments a pre-formed porous matrix layer is formed on an emitting surface of a light emitting diode. In any case, the matrix precursor may be or include one or more of the materials identified above as suitable for use in the porous matrix.

[0033] In some instances the matrix precursor may be in the form of particles of one or more of the materials previously identified as suitable for use in the porous matrix. In such instances, a pre-formed porous matrix layer may be formed by a method that includes depositing particles of the matrix precursor on a support in any suitable manner. For example, in some embodiments particles of a matrix precursor may be deposited on a support

via drop-casting, spin-coating, ink-jet printing, spraying, combination thereof, and the like. In such instances, a dispersion, emulsion, and/or suspension particles of a matrix precursor and a liquid phase component may be provided, and used to carry out the above-noted deposition of such particles e.g., via drop-casting, spin-coating, spraying, combinations thereof, and the like.

[0034] Following its deposition, the matrix precursor may be subject to processing to produce a pre-formed porous matrix layer. For example where a suspension, dispersion, emulsion, etc. including a liquid phase is used to deposit particles of matrix precursor on a support, a drying process may be carried out to remove or at least substantially remove the liquid phase. Following such drying, one or more layers of the particles of matrix precursor may be present on the support. For example, in some instances a monolayer of matrix precursor particles may be present after drying is carried out. In other instances, multiple layers of matrix precursor particles may be disposed on the support. In such instances it may be understood that deposition of the matrix precursor particles results in the formation of a precursor film having a thickness that is larger than the particle size of the matrix precursor particles.

[0035] Following deposition of the matrix precursor particles, a thermal treatment process may also be carried out to fuse or otherwise join at least a portion of the deposited particles of matrix material precursor to one another, resulting in the formation of a porous matrix. For example, the remaining particles may be heated to or just above their glass transition temperature (T_g). Such heating may cause at least a portion of the particles to melt and flow into adjacent particles, resulting in the formation of a matrix including pore structures. Similarly, in some embodiments thermal treatment of deposited particles of a matrix precursor may involve heating the matrix precursor to or slightly above (e.g., less than about 5%) the softening point of a matrix precursor material (i.e., the material(s) used to form the matrix pre-cursor particles). At such temperature, the surface of the particles of the matrix precursor may soften and adhere to nearby (e.g., adjacent) particles. With that in mind, Table 2 below provides bulk densities and softening points for various materials that may be used to form a pre-formed porous matrix layer.

TABLE 2: Properties of Various Matrix Precursor Materials.

Material	Bulk Density (g/cm³)	Softening Point (°C)
Vitreous Silica	2.2	1580-1670
Soda-lime silicate	2.49	750
Sodium Borosilicate	2.23	820
Lead-alkali silicate	3.02	677
Aluminosilicate	2.64	910
Optical Glass	2.51	719

Alternatively or additionally, the remaining particles may be sintered. In any case, following such heat treatment the particles may be cooled and/or quenched, resulting in the formation of a porous matrix.

[0036] The time and temperature used during such thermal treatment may be controlled to ensure sufficient bonding between particles of matrix precursor, but to avoid transforming the particles of matrix material into a substantially solid material, i.e, a solid body having a density greater than or equal to about 90% of the theoretical density the material used to form the matrix precursor. For example where particles of vitreous silica are used as a matrix precursor, the density of the pre-formed porous matrix layer may be less than about 90% of 2.2 g/cm³ (i.e., less than 90% of the theoretical density of silica).

[0037] As may be appreciated, the dimensions (e.g., particle size, longest dimension, etc.) of the particles of matrix precursor material may have an impact on the microstructure of a pre-formed porous matrix, and in particular on the type and/or configuration of the pore structures present therein. For example if relatively large particles of matrix precursor material are used, a porous matrix with relatively few but relatively large pore structures may result. Alternatively if relatively small particles of matrix precursor material are used, a porous matrix with relatively many but relatively small pore structures may result. It may therefore be desirable to utilize particles of matrix precursor particles that have a desired particle size and/or particle size range, so as to attain a porous matrix that includes pore structures that are of a desired size and/or configuration.

[0038] With the foregoing in mind, the particles of matrix precursor material may have any suitable particle size. For example, the particles of matrix precursor material may have an average particle size ranging from about 50 nanometers (nm) to about 100 microns (μm), such as from about 50 nm to about 10 μm, or even about 50nm to about 1 μm.

[0039] The (pre-formed) porous matrix layers described herein may be formed to any suitable thickness. For example, in some embodiments the pre-formed porous matrix layer may have a thickness ranging from the thickness of a monolayer of matrix precursor particles (which may have a particle size within the above noted ranges) to a total thickness of about 500 microns or more. Without limitation, in some embodiments, the pre-formed porous matrix layers described herein may have a total thickness ranging from about 1 μm to about 250 μm , such as about 10 to about 150 μm , about 50 to about 100 μm , or even about 70 to about 100 μm .

[0040] As may be appreciated, the thickness and refractive index of the pre-formed matrix layer may have an impact on the optical performance of the wavelength converters described herein. For example, such properties may impact the manner and degree to which primary and secondary light are scattered by the wavelength converters described herein. More specifically, the difference in the index of refraction of the porous matrix material as compared to that of a material that is infiltrated into the pore structures thereof can affect light scattering. Depending on the circumstances, this phenomenon may be leveraged to improve the conversion of the amount of primary (e.g., blue) light that is converted to secondary light. That is, such scattering may be utilized to enhance conversion efficiency by dispersing incident primary light within the wavelength converter, thereby increasing the probability that such light will be incident on a wavelength conversion material and be converted to secondary light. However, such scattering can also result in light loss, and therefore it may be desirable to optimize the refractive index, porosity, etc. of the pre-formed porous matrix (and a wavelength conversion material infiltrated therein) so as to achieve high light conversion efficiency while reducing or minimizing losses due to scattering.

[0041] As previously noted the wavelength converters of the present disclosure may include one or more types of wavelength conversion materials that are present within at least a portion of the pore structures of a porous matrix, such as a pre-formed porous matrix layer. In various embodiments, the wavelength conversion materials are in the form of wavelength converting particles, which may be added to a pre-formed porous matrix layer in any suitable manner.

[0042] For example, one or more wavelength converting particles may be infiltrated into at least a portion of the pore structures by depositing a dispersion, emulsion, suspension, etc. containing the wavelength converting particles onto a surface of a pre-formed porous matrix layer. In such instances, the liquid phase of such dispersion, emulsion, suspension, etc. may be selected such that it can wet the surfaces of the pre-formed porous matrix layer,

and in particular the surfaces within and/or leading into the pore structures in the porous matrix layer. In that way, the liquid phase may facilitate infiltration of the wavelength converting particles into the pore structures of the porous matrix layer. Alternatively or additionally, once wavelength converting particles are deposited on a surface of a porous matrix layer, the resulting precursor may be exposed to a vacuum to draw the wavelength converting particles into the pore structures of the porous matrix layer. In any case, at least a portion of the wavelength converting particles may be present within at least a portion of the pore structures of the porous matrix layer.

[0043] Phosphor particles are one example type of wavelength converting particles that may be used in the wavelength converting compositions described herein. As may be generally understood by one skilled in the art, a phosphor is a compound capable of emitting, upon excitation by an external energy source (e.g., primary light), useful quantities of radiation (e.g., secondary light) in the visible and/or ultraviolet region of the electromagnetic spectrum. Examples of suitable phosphor particles that may be used in the wavelength conversion compositions described herein include but are not limited to particulate forms of yellow phosphor, green phosphor, red phosphor, and/or combinations thereof. Of course, these example phosphor types are not limiting, and any suitable phosphor particles may be used in accordance with the present disclosure.

[0044] Other non-limiting examples of phosphor particles that may be used in accordance with the present disclosure include particulate forms of one or more inorganic phosphors such as oxyfluoride, nitride (including oxynitride), and oxide phosphors (e.g., aluminate garnets, silicates etc.). Other non-limiting examples of suitable phosphor particles include particulate forms of phosphors containing one or more of cerium-activated yttrium aluminum garnets (YAG:Ce), cerium-activated yttrium gadolinium aluminum garnets (YGdAG:Ce), cerium-activated lutetium aluminum garnets (LuAG:Ce), europium- or cerium-activated alkaline earth (AE) silicon oxynitride (AE-SiON:Eu, where AE designates at least one element selected from Ba, Sr, and Ca), europium- or cerium-activated metal-SiAlON (M-SiAlON, where M is chosen from alkali ions, rare earth ions, alkaline earth ions, Y, Sc, and combinations thereof), and the like.

[0045] In some embodiments the phosphor particles may be doped with a small amount of an activator ion such as but not limited to cerium, gadolinium, scandium, europium, combinations thereof, and the like. When used, the amount of activator ion may vary widely, e.g., from greater than 0 to about 10 atomic %, such as about 1 to about 5 atomic %, or even about 1 to 2 atomic percent. In one non-limiting embodiment, the wavelength

converting particles described herein include phosphor particles that include a combination of two or more of doped YAG, doped LuAG, doped silicates, and doped nitride phosphors.

[0046] The particle size and/or particle size distribution of the phosphor particles may impact the degree to which such particles may infiltrate into the pore structures of a porous matrix, and therefore may potentially affect their distribution within the wavelength converters described herein. It may therefore be desirable to select phosphor particles for use in the wavelength converting compositions described herein based at least in part on their particle size/distribution, either independently or in relation to the particle size/distribution of other wavelength converting particles, and/or the size of pore structures that are present in the porous matrix. Therefore in some embodiments the phosphor particles described herein may have a particle size ranging from about 1 to about 250 microns, such as about 10 to about 100 microns, about 10 to about 50 microns, or even about 20 to about 40 microns. In some embodiments, the particle size of the phosphor particles ranges from about 20 to about 40 microns. In these or other non-limiting embodiments the particle size of the phosphor particles may be larger or smaller than another type of wavelength converting particles within pore structures of a porous matrix, such as but not limited to quantum dot particles that may be included in the wavelength converters described herein. Nanophosphors having a particle size of about 100 to about 200 nanometers (nm) may also be used.

[0047] As used herein, quantum dot particles (i.e., semiconductor nanocrystals) are another example type of wavelength converting particles that may be used to convert light from one wavelength or wavelength range to another wavelength or wavelength range in accordance with the present disclosure. In general, the quantum dot particles described herein may include quantum dots, which may be understood as semiconductor nanocrystals that are smaller than the Bohr radius of their corresponding bulk semiconductor. It should be understood that the wavelength converting particles of the present disclosure are not limited to any particular type of quantum dot particles, so long as such particles are capable of converting light from a first wavelength or wavelength range to a second wavelength of wavelength range.

[0048] For the sake of clarity and ease of understanding, the terms “core quantum dot particles” and “core quantum dots” are used herein to refer to semiconductor nanocrystals that may or may not be over coated with one or more organic ligands to prevent agglomeration, facilitate dispersion, and/or to passivate non-radiative recombination centers on the surface. In contrast, the terms “core/shell quantum dot particles” and “core/shell quantum dots” are used to refer to semiconductor nanocrystal particles in which a first

semiconductor nanocrystal forms a “core” that is over coated with a “shell” of a larger bandgap semiconductor material. Like core quantum dot particles, core/shell quantum dot particles may or may not be further over coated with one or more organic ligands to prevent agglomeration, facilitate dispersion, and/or to passivate non-radiative centers. Moreover, the term “quantum dot beads” is used to refer to particles that include a bead matrix into which a plurality of core quantum dot particles and/or core/shell quantum dot particles are incorporated. It should therefore be understood that the term “quantum dot particles” encompasses core quantum dot particles, core/shell quantum dot particles, and quantum dot beads unless otherwise indicated.

[0049] Some examples of suitable core quantum dots include particulate forms of one or more luminescent semiconductor nanocrystals. Specific non-limiting examples of suitable core quantum dots include particulate forms of one or more of the following semiconductors: CdS, CdSe, CdTe, ZnS, ZnSe, ZnTe, InP, InAs, InSb, AlP, AlS, AlAs, AlSb, GaN, GaP, GaAs, GaSb, PbS, PbSe, Si, Ge and combinations thereof. In some embodiments, the wavelength converting compositions of the present disclosure include core/shell quantum dot particles including nanocrystalline indium phosphide. Without limitation, the quantum dot particles described herein are preferably cadmium free.

[0050] Although the present disclosure envisions the use of core quantum dot particles such as those noted above alone, such particles may suffer from one or more drawbacks which may make them difficult to handle or process without materially impacting their ability to convert incident light. The core quantum dot particles may also exhibit relatively low quantum efficiencies due to non-radiative electron-hole recombination occurring at defects and dangling bonds in or at their surface. Exposure to moisture and oxygen may result in oxidation of the surface of the particle and may adversely modify their performance.

[0051] To address this issue, core quantum dot particles may be coated with one or more “shells,” so as to form core/shell quantum dot particles. In such particles, the “core” is a core quantum dot particle such as those noted above, and the “shell” is an inorganic and/or organic material that individually coats or encapsulates the core quantum dot particle. Suitable materials for the core of core/shell quantum dots include the core quantum dot particles noted above. Suitable materials for forming the shell(s) of a core/shell quantum dot particle include one or more semiconductor materials having a larger bandgap than the core. Examples of such materials include ZnS and/or a combination of ZnSe and ZnS. Of course,

other semiconductor materials may be used as a shell of a core/shell quantum dot particle, provided that the shell material has a larger bandgap than the core.

[0052] The above noted shell materials may be applied to the core using any technique known in the art. By way of example, the core may be coated with one or more shells using wet chemical synthesis, successive ionic layer adsorption and reaction (SILAR), and the like. In any case the thickness of the shell may vary widely, and may range from about 1 to about 500nm, such as about 10-500nm, or even about 100 to about 500nm. In some embodiments, one or more shells are formed around a core quantum dot particle. For example the core quantum dot particles may be coated with 1, 2, 3 or more shells, wherein each shell may be selected from the aforementioned shell materials

[0053] In some embodiments the core quantum dot and/or core/shell quantum dot particles may be used and/or provided in the form of a colloidal dispersion, which may be used to infiltrate pore structures of a porous matrix consistent with the present disclosure with quantum dot particles. For example and consistent with the above description, a colloidal dispersion of core quantum dot particles and/or core/shell quantum dot particles may be applied to a surface of a pre-formed porous matrix. Following such application, the particles in the dispersion may infiltrate into the pore structures of the pre-formed porous matrix, as discussed above. Alternatively or additionally, such infiltration may be facilitated in various ways, such as by applying a vacuum to draw the core quantum dot particles and/or core/shell quantum dot particles into the pore structures of the porous matrix.

[0054] Although the present disclosure contemplates the use of core quantum dot particles and core/shell quantum dot particles as wavelength converting particles, use of such particles is not required. Indeed in some embodiments the quantum dot particles of the present disclosure may be in the form of quantum dot beads, wherein each bead comprises a bead matrix that encapsulates a plurality of core quantum dot particles, core/shell quantum dot particles, or a combination thereof. In some embodiments the bead matrix is an optically transparent medium, such as but not limited to an optically transparent resin, polymer, monolith, glass, sol gel, epoxy, silicone, (meth)acrylate or the like, or may include silica. Non-limiting examples of suitable bead matrix materials include acrylate polymers such as polymethyl(meth)acrylate, polybutylmethacrylate, polyoctylmethacrylate, alkylcyanoacrylates, polyethyleneglycol dimethacrylate, lauryl methacrylate, polyvinylacetate etc., epoxides such as EPOTEK 301 A+B Thermal curing epoxy, EPOTEK OG112-4 single pot UV curing epoxy, or EX0135A and B Thermal curing epoxy, polyamides, polyimides, polyesters, polycarbonates, polythioethers, polyacrylonitrils,

polydienes, polystyrene polybutadiene copolymers (Kratons), pyrenes, poly-para-xylylene (parylenes), silica, silica-acrylate hybrids, polyetheretherketone (PEEK), polyvinylidene fluoride (PVDF), polydivinyl benzene, polyethylene, polypropylene, polyethylene terephthalate (PET), polyisobutylene (butyl rubber), polyisoprene, and cellulose derivatives (methyl cellulose, ethyl cellulose, hydroxypropylmethyl cellulose, hydroxypropylmethylcellulose phthalate, nitrocellulose, and combinations thereof.

[0055] Although a wide variety of bead matrixes are envisioned, use of a bead matrix that has a refractive index that significantly differs from that of the porous matrix material may introduce interfaces with the porous matrix material that may scatter, reflect, and/or refract light within the wavelength converter. Therefore in some embodiments the bead matrix and porous matrix material are selected such that they have relatively close or even identical refractive indices. For example, in some embodiments the porous matrix may exhibit a first refractive index n_1 , the bead matrix may exhibit a second refractive index n_2 , and n_1 may differ from n_2 by less than or equal to 15%, 10%, 5%, 1%, or even 0.1%. In some embodiments, n_1 equals n_2 . In some embodiments, the bead matrix exhibits a refractive index n_1 ranging from about 1.2 to about 2.1, such as above 1.4 to about 1.6, and the quantum dot beads exhibit a refractive index n_2 that is the same as n_1 , or differs from n_1 within the foregoing ranges.

[0056] Like core quantum dot particles, the quantum dot beads described herein may also be coated with one or more layers or shells of an inorganic or organic material, e.g., for the purpose of limiting contact of the quantum dot particles with oxygen. In this regard any suitable material may be used to coat the quantum dot beads, such as but not limited to the nitrides, oxides and organic materials identified above as being suitable for coating core quantum dot particles.

[0057] The beads may not interact with a porous matrix in the same manner as a colloidal dispersion of core and/or core/shell quantum dots. For example, in instances where quantum dot beads are applied to a surface of a porous matrix material, they may lack a liquid or other interfacial medium that facilitates their infiltration into the pore structures of the porous matrix. In such instances it may be desirable to facilitate infiltration of the quantum dot beads into such pore structures through other means. For example and consistent with the foregoing description, a vacuum may be applied to draw the quantum dot beads into at least a portion of the pore structures in the porous matrix.

[0058] As shown above a wide variety of core quantum dot particles, core/shell quantum dot particles, and quantum dot beads may be used as wavelength converting

particles in wavelength converters consistent with the present disclosure. As specific non-limiting examples of suitable core quantum dot particles, core/shell quantum dot particles, and quantum dot beads that may be used, mention is made of the core quantum dot particles, core/shell quantum dot particles, and quantum dot beads described in U.S. Patent Publication No. 2013/0189803, the entire content of which is incorporated herein by reference. Without limitation, the quantum dot particles described herein are preferably one or more types of quantum dot beads.

[0059] As will also be appreciated, the particle size of quantum dot beads may impact their ability to infiltrate into the pore structures of a porous matrix material. It may therefore be desirable to select and or use quantum dot beads based at least in part on their particle size, which is preferably less than an average size of the pore structures of a porous matrix. For example, in some embodiments the quantum dot beads may have a size that is about 10, 20, 30, 40, 50, 60, 70, or even 80% smaller (or less) than the average size of the pore structures within a porous matrix. In that regard the quantum dot beads noted above may have a particle size ranging from about 1 to about 250 microns, such as about 1 to about 100 microns or even about 1 to about 50 microns. In these or other non-limiting embodiments the particle size of the quantum dot beads may be larger or smaller than another type of wavelength converting particles within the polymeric bead matrix and matrix precursor, such as but not limited to the phosphor particles noted above.

[0060] In some embodiments that particles of wavelength conversion materials may be selected and/or configured so as to fill or otherwise occupy a desired amount of the pore structures within a pre-formed porous matrix. For example, in some instances the particles of wavelength conversion material may fill or otherwise occupy from greater than or equal to about 10%, 25%, 50%, 75%, 90%, 95%, 99% or more of the pore structures in a pre-formed porous matrix. Without limitation, in some embodiments from greater than or equal to about 10% to less than or equal to about 90%, such as from about 25% to about 90%, about 50% to about 90% or even about 70% to about 90% of the pore structures in a pre-formed porous matrix consistent with the present disclosure are filled or otherwise occupied with particles of a wavelength conversion material.

[0061] As may also be appreciated, as relatively small particle size of the particles of wavelength converting materials used herein may present processing and/or other challenges. For example, as the particle size of the particles of wavelength converting materials decreases, the particles may tend to agglomerate together to form agglomerates, wherein the agglomerates are of a size that is larger (e.g., several times larger) than individual

particles of the wavelength conversion material. As such agglomerates may exhibit optical and/or other properties that differ from the properties of individual (i.e., non-agglomerated) particles of wavelength conversion material, it may be desirable to take steps to limit and/or prevent agglomeration of the particles of wavelength conversion materials used in the context of the present disclosure. For example and as noted above, it may be desirable to coat or otherwise treat the particles of wavelength conversion materials (e.g., quantum dot particles) with one or more organic or inorganic ligands to limit and/or prevent their agglomeration, facilitate dispersion, and/or to passivate non-radiative recombination centers on the surfaces thereof. Of course, such treatment may not be necessary in all instances, such as when particles of wavelength conversion materials that do not tend to agglomerate are used.

[0062] With the foregoing in mind, in some embodiments of the present disclosure infiltration of particles of wavelength conversion material into a pre-formed porous matrix may result in the formation of a wavelength converter that includes non-agglomerated (i.e., individual) particles of wavelength conversion material within at least a portion of the pore structures in the pre-formed porous matrix. In some instances, the particles of wavelength conversion material within the pore structures comprise, consist essentially of, or consist of non-agglomerated particles of wavelength conversion material, such as but not limited to non-agglomerated quantum dot particles.

[0063] In some embodiments the wavelength converters described herein may include one or more than one type of wavelength converting particles within at least a portion of the pore structures of a porous matrix layer. For example the wavelength converters described herein may include at least first and second types of wavelength converting particles, wherein the first type of wavelength converting particles includes phosphor particles selected from those described above, and the second type of wavelength converting particles includes one or more types of quantum dot particles, such as the core quantum dot particles, core/shell quantum dot particles, or quantum dot beads described above. Without limitation, in some embodiments the first type of wavelength converting particles include a plurality of at least one type of the phosphor particles described above, and the second type of wavelength converting particles include a plurality of at least one type of the quantum dot beads described above. For example, in some instances mint green broadband phosphor particles may be used in combination with red quantum dot beads to produce a warm white light from a light source such as an LED. In other non-limiting embodiments, yellow broadband phosphor particles may be used in combination with green and/or red quantum dot beads, which may broaden the white light spectrum. It should therefore be understood that the

quantum dot beads described herein may be used to tune or adjust the light output produced by a light source and/or phosphor particles

[0064] The total amount of wavelength converting particles in the wavelength converters described herein may vary widely. In some embodiments, the wavelength converting particles may be present in the wavelength converters described herein in an amount ranging from about 1 to about 70 % by weight, such as about 1 to about 50%, about 5 to about 40%, about 10 to about 30%, or even about 20 weight %, relative to the total weight of the wavelength converter.

[0065] In some embodiments the wavelength converters described herein include a porous matrix layer that includes a plurality of pore structures, wherein at least a portion of the pore structures are infiltrated with first and second types of wavelength converting particles. In such instances, the first type of wavelength converting particles may include phosphor particles and the second type of wavelength converting particles include quantum dot particles (e.g. in the form of core quantum dot particles, core/shell quantum dot particles, and quantum dot beads). As noted above, the amount of phosphor particles and quantum dot particles may vary widely, either independently or with respect to one another. For example the quantum dot particles may be present in an amount ranging from about 10 to about 50 weight % (e.g., about 10 to about 40 weight % or even about 10 to about 20 weight %), relative to the total weight of the wavelength converter, whereas the phosphor particles may be present in an amount ranging from about 1 to about 20 weight % (such as about 10 to about 20 weight %) of the wavelength converter.

[0066] Another aspect of the present disclosure relates to lighting devices that include a wavelength converter consistent with the present disclosure. Although the present disclosure contemplates the use of the wavelength converters and wavelength converting compositions in a wide variety of lighting devices, such converters and converting compositions may be particularly suitable for use in lighting devices that include a solid state light source such as a light emitting diode package. In such application, the wavelength converters described herein may convert all or a portion of the emitted primary light to secondary light.

[0067] Reference is therefore made to FIG. 1, which depicts one example of a lighting device that includes a wavelength converter consistent with the present disclosure. As shown, lighting device 100 includes a light source 101. While a wide variety of light sources may be used as light source 101, for the sake of illustration the present disclosure will

focus on embodiments in which light source 101 is an LED. Therefore and as shown in FIG. 1, light source 101 includes light emitting surface 102.

[0068] In various embodiments light source 101 is an LED that is configured to emit primary light. For example, light source 101 may be an LED configured to emit light in the ultraviolet, visible, or infrared region of the electromagnetic spectrum. Without limitation, light source 101 in some embodiments is configured to emit blue light. Regardless of its nature, light source 101 may emit primary light (not shown) from emitting surface 102 thereof. Subsequent to emission by light source 101, the primary light may impinge on wavelength converter 103.

[0069] Consistent with the foregoing discussion, wavelength converter 103 may include a porous matrix layer 104 that includes one or more pore structures therein (not shown). Wavelength converter 103 may also include one or more wavelength conversion materials, such as wavelength converting particles 105. In some embodiments, wavelength converting particles 105 may be present within at least a portion of the pore structures in porous matrix layer 104, as previously described. In any case, wavelength converting particles 105 may include one or more types of particles that are capable of converting incident primary light to secondary light. Non-limiting examples of such particles include phosphor particles and quantum dot particles, as previously described. Without limitation, in some embodiments at least a portion of wavelength converting particles 105 are quantum dot particles, such as but not limited to core quantum dot particles, core/shell quantum dot particles, and quantum dot beads, as previously described.

[0070] It is noted that for the sake of illustration and ease of understanding, light source 100 is depicted in FIG. 1 as including a single wavelength converter 103. It should be understood that this is exemplary only, and that more than one wavelength converter 103 may be used. For example, in some embodiments lighting device 100 may include a first wavelength converter 103 disposed directly on an emitting surface 102 of light source 101. Although not shown, in such embodiments one or more additional (e.g., second, third, fourth, etc.) wavelength converters may be disposed on (e.g., directly on) an upper surface of wavelength converter 103.

[0071] For example, in some embodiments a plurality of wavelength converters may be used, e.g., in which a first wavelength converter is formed directly on light emitting surface 102, and a second wavelength converter is formed on or directly on an upper surface of the first wavelength converter. In such instances at least one of the first and second wavelength converters may include a porous matrix infiltrated with wavelength converting

particles, as discussed above. Without limitation, in some embodiments the first wavelength converter includes a first porous matrix infiltrated with first wavelength converting particles and the second wavelength converter includes a second porous matrix infiltrated with second wavelength converting particles, wherein the first and second porous matrix materials are the same or different from one another, and the first and second wavelength converting particles are the same or different from one another.

[0072] Alternatively or additionally, in some embodiments more than one type of wavelength converting particles may be used as wavelength converting particles 105. For example, in some embodiments wavelength converting particles 105 may include first and second wavelength converting particles that differ from one another. Without limitation, in some embodiments wavelength converting particles 105 include first and second wavelength converting particles that are different types of quantum dot particles. In such instances the first and second wavelength converting particles may be chosen from the example quantum dot materials noted above, and/or from other suitable quantum dot materials. Regardless of their composition, the first and second wavelength converting particles may be infiltrated into porous matrix layer 104, as described above.

[0073] As further shown in FIG. 1, lighting device 100 may further include optional component 107. In some embodiments, optional component 107 may function to seal one or more exposed surfaces of wavelength converter 103, thereby insulating porous matrix 104 and wavelength converting particles 105 from the ambient environment. In such instances, optional component 107 may be understood to be a sealing layer. As may be appreciated, such a sealing layer may be of use in instances where wavelength converting particles 105 may include or be formed from elements and/or compounds that can react with substances (e.g., oxygen) in the ambient atmosphere, potentially hindering their ability to convert primary light from light source 101 to secondary light.

[0074] With the foregoing in mind, optional component 107 may be formed from any suitable sealing material. Non-limiting examples of such materials include transparent polymers such as a transparent silicone, transparent epoxy, or the like. Alternatively or additionally, optional component 107 may in the form of an optical component, such as but not limited to a lens. It should therefore be understood that while optional component 107 is depicted in FIG. 1 in the form of a layer, it may have any suitable geometry. For example, optional component 107 may have a lenticular or other geometry, such as the geometry shown in FIG. 4. In either case, optional component 107 may be adhered to the surface of wavelength converter 103 with or without the use of an adhesive, such as an optical glue.

[0075] It is noted that in the interest of clarity and ease of understanding, lighting device 100 is illustrated in FIG. 1 with limited components. It should be understood that the lighting devices described herein are not limited to the illustrated components, and may include various other elements as would be understood by one of ordinary skill in the art. For example, in some embodiments lighting device 100 may include and/or be formed on an underlying substrate, such as a circuit board or other driving electronics as would be understood by those of ordinary skill in the art of light emitting devices. In that regard reference is made to FIG. 4, which depicts another example of another lighting device consistent with the present disclosure. As shown, lighting device 400 includes light source 101, wavelength converter 103, and optional component 407, the nature and function of which are previous described. In addition, lighting device 400 includes support 401. Without limitation, support 401 may be in the form of a circuit board containing electrical circuits, contacts, etc. for driving light source 101. Alternatively or additionally, support 401 be a support structure that provides mechanical support for other components in light source 100, e.g., an LED lighting package. Moreover and as also shown in FIG. 4, lighting device 400 may include optional component 407, which may be substantially similar in structure, materials, and function as optional component 107, except insofar as it encapsulates the sides of wavelength converter 103 and light source 101.

[0076] Another aspect of the present disclosure relates to methods of manufacturing wavelength converters that include a porous matrix layer. In the regard reference is made to FIG. 2, which is a flow chart of example operations consistent with one embodiment of a method of making a wavelength converter consistent with the present disclosure. For the sake of illustration and ease of understanding, the operations of FIG. 2 will be described in conjunction with FIGS. 3A-3D, which stepwise illustrate the formation of a wavelength converter consistent with the present disclosure on a light emitting surface of an LED. It should be understood that the operations of FIG. 2 and the illustrations shown in FIGS. 3A-3D are for the sake of example only, and that wavelength converters consistent with the present disclosure may be manufactured in a different manner. For example while FIGS. 3A-3D depict the formation of a wavelength converter directly on a light emitting surface of an LED, it is possible to form wavelength converters consistent with the present disclosure separately, i.e., without the use of a light source. Moreover while FIGS. 3A-3D depict the formation of a single wavelength converter on a single light source, one of ordinary skill in the art will understood that the methods described herein may be scaled to produce multiple

wavelength converters, e.g., on an array of light sources (an array of LEDs or LED packages.)

[0077] Turning now to FIG. 2, as shown method 200 begins at block 201. The method may then proceed to block 203, pursuant to which one or more supports may be provided. As noted above any suitable support may be used, such as a substrate, circuit board, light emitting surface of a light source, etc. Without limitation in some embodiments the support provided pursuant to block 203 is a light emitting surface of a light source, such as an LED. This operation is depicted in FIG. 3A, which illustrates the provision of light source 101 including a light emitting surface 102, as previously described. For example, in some embodiments one or more LEDs, LED packages, arrays of LED packages, etc. may be provided pursuant to block 203, e.g., in isolated form or supported by another component such as a circuit board. In any case, the light source(s) 101 may be configured to emit primary light in a first wavelength, wavelength range, as noted above.

[0078] The method may then proceed to block 205, pursuant to which a porous matrix layer including pore structures may be formed on the support. For example, pursuant to block 205 in some embodiments a pre-formed porous matrix layer may be formed directly on a light emitting surface 102 of a light source 101. This concept is shown in FIG. 3B, which illustrates the formation of porous matrix layer 104 on light emitting surface 102. As shown in this embodiment, porous matrix layer 104 does not include any wavelength converting particles at this stage, and therefore may be understood to be a pre-formed porous matrix layer as described above. With that in mind, a porous matrix layer may be provided pursuant to block 205 in any suitable manner. For example and as described above, in some embodiments the porous matrix layer may be formed by depositing particles of a porous matrix precursor on a support, such as light emitting surface 102, and processing the resulting precursor (e.g., via heat treatment, sintering, or the like) to form a porous matrix layer. In such instances, the particles of porous matrix precursor may be particles of the materials previously identified herein as being suitable for use in porous matrix layer 104.

[0079] Once a porous matrix layer including pore structures has been formed pursuant to block 205, method 200 may proceed to block 207. Pursuant to block 207, one or more wavelength converting particles may be infiltrated into at least a portion of the pore structures of the porous matrix layer. The nature and configuration of such particles has been previously described, and is therefore not reiterated in the interest of brevity. Without limitation, in some embodiments the wavelength converting particles infiltrated into the pore structures of the porous matrix layer pursuant to block 207 are or include quantum dot

particles, such as core quantum dots, core/shell quantum dots, quantum dot beads, or a combination thereof. This concept is illustrated in FIG. 3C, which depicts the addition of wavelength converting particles 105 to porous matrix layer 104.

[0080] As discussed previously, a number of different methods may be used to infiltrate wavelength converting particles into at least a portion of the pore structures of a porous matrix layer. For example, such infiltration may be accomplished by depositing a dispersion, emulsion, suspension, etc. containing wavelength converting particles onto a surface of a porous matrix layer, and allowing the particles to infiltrate into the pore structures thereof over time. As noted previously, such infiltration may be aided by the use of a liquid phase (e.g., toluene or another organic solvent) that can wet the surface of the porous matrix layer, and in particular the surfaces of the pore structures therein. Alternatively or additionally, once wavelength converting particles are deposited on a surface of a porous matrix layer, the resulting precursor may be exposed to a vacuum to draw the wavelength converting particles into the pore structures of the porous matrix layer. In any case, at least a portion of the wavelength converting particles may be present within at least a portion of the pore structures of the porous matrix layer, resulting in the formation of wavelength converter 103, as shown in FIG. 3.

[0081] Once the operations of block 207 are complete, method 200 may proceed to optional block 209. Pursuant to optional block 209, the surface(s) of the wavelength converter produced pursuant to blocks 205 and 207 may be sealed and/or covered, e.g., with an optional component as described above. This concept is illustrated in FIG. 3D, which illustrates an embodiment in which an upper surface of wavelength converter 103 is covered with optional component 107.

[0082] For example, one or more surfaces of the wavelength converter may be sealed with a sealing material, such as the sealing materials noted above. Formation of the sealing layer may be accomplished, for example, via drop casting, ink-jet printing, spin coating, combinations thereof, and the like. Alternatively or additionally, one or more surfaces of the wavelength converter may be covered with another type of component, such as a lens as previously described. In instances where the lens is formed from a polymeric material, it may be formed by depositing such a polymeric material or a precursor thereof on a surface of the wavelength converter, e.g., by spin coating, ink-jet printing, spin coating, or the like. Alternatively, a lens may be formed separately, and then coupled (e.g., with an adhesive) to one or more surfaces of a wavelength converter, lighting device, or a combination thereof. In the latter case, coupling of a lens to a wavelength converter may be

accomplished using so-called “pick and place” technology, wherein a lens may be picked up by a placement arm, appropriately positioned on a surface of a wavelength converter, and bonded into place (e.g., with an adhesive).

EXAMPLES

[0083] For the sake of illustration the present disclosure will now proceed to describe several examples in which a combination of wavelength converting particles are used to form a single layer wavelength converter consistent with the present disclosure. It should be understood that the following examples are representative only, and should not be considered to represent the entire scope of the invention described herein.

[0084] To investigate performance, three sample wavelength converters consistent with the present disclosure were manufactured. In the first sample, a porous matrix of α -alumina particles was used. In the second and third samples, porous matrices formed from aluminum nitride and silica were used. In all of the samples, the porous matrix was infiltrated with red quantum dots.

[0085] In each example, the porous matrix was formed by dispersing particles of matrix precursor material (i.e., α -alumina particles, aluminum nitride particles, silica particles) in ethanol to form a dispersion. Each dispersion was then drop cast on a substrate, which was either a glass slide or aluminum foil. The resulting films were each covered with a cap containing a small orifice, and were slowly dried to remove the liquid phase (i.e., ethanol) to form a matrix precursor. Subsequently, the matrix precursors were heat treated to sinter at least a portion of the particles therein to one another, resulting in the formation of pre-formed porous matrices including pore structures. Observation of the pre-formed porous matrices revealed that they appeared to contain pore structures having a size ranging from about 1 to about 100 microns.

[0086] To infiltrate the pre-formed porous matrices with a wavelength conversion material, a dispersion of red quantum dots in a liquid phase (toluene) was prepared. The dispersion was drop-cast onto the surface of each of the pre-formed porous matrices in an inert atmosphere. Following drop casting, the samples were allowed to dry, resulting in the formation of a wavelength converter. Observation of the sample wavelength converters revealed infiltration of the red quantum dots into the pore structures of the pre-formed porous matrix.

[0087] As may be appreciated from the foregoing, the technologies of the present disclosure can enable the formation of wavelength converters that include quantum dots via relatively straightforward techniques that may be scaled up for commercial production.

Moreover, the wavelength converters can exhibit desirable performance characteristics, and may enable lighting designers to tailor the light output of a lighting device, potentially without having to rely on complex and expensive manufacturing techniques.

[0088] Other than in the examples, or where otherwise indicated, all numbers expressing endpoints of ranges, and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about." Accordingly, unless indicated to the contrary, the numerical parameters set forth in the specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by the present disclosure. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should be construed in light of the number of significant digits and ordinary rounding approaches.

[0089] Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the present disclosure are approximations, unless otherwise indicated the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements.

[0090] Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the invention being indicated by the following claims.

WHAT IS CLAIMED IS:

1. A wavelength converter, comprising:
a pre-formed porous matrix layer, the pre-formed porous matrix layer comprising pore structures; and
particles of a wavelength conversion material, wherein said particles of wavelength conversion material comprise non-agglomerated quantum dot particles, and at least a portion of the particles of wavelength conversion material are present within said pore structures.
2. The wavelength converter of claim 1, wherein:
the pre-formed porous matrix layer comprises particles of a matrix precursor material and a network of said pore structures; and
at least a portion of said particles of matrix precursor are sintered to one another to define at least a portion of said network of pore structures.
3. The wavelength converter of claim 1, wherein:
said pre-formed porous matrix layer is formed from a matrix precursor material; and
said pre-formed porous matrix layer has a density that is less than 90% of a theoretical density of said matrix precursor material.
4. The wavelength converter of claim 1, wherein said pre-formed porous matrix layer is formed from a matrix precursor material selected from the group consisting of aluminum oxide, an aluminosilicate, silicon dioxide, soda-lime silicate, sodium-borosilicate, lead-alkali silicate, titanium dioxide, lutetium aluminum garnet, yttrium aluminum garnet, zinc oxide, and zirconium oxide, and combinations thereof.
5. The wavelength converter of claim 1, wherein said quantum dot particles are selected from the group consisting of core quantum dots, core/shell quantum dots, quantum dot beads, and combinations thereof.
6. The wavelength converter of claim 1, wherein said particles of wavelength conversion material comprise particles of a first wavelength conversion material and particles

of a second wavelength conversion material, wherein the first and second wavelength conversion materials differ from one another.

7. The wavelength converter of claim 1, wherein said particles of wavelength conversion material occupy from greater than or equal to about 10% to less than or equal to about 90% of said pore structures in said pre-formed porous matrix.

8. The wavelength converter of claim 1, wherein said pre-formed porous matrix layer is formed from a matrix material having a thermal conductivity greater than or equal to about 0.2 W/mK.

9. The wavelength converter of claim 1, wherein said particles of wavelength conversion material consist essentially of said non-agglomerated quantum dot particles.

10. A lighting device comprising:

a light source having a light emitting surface; and

a wavelength converter directly on said light emitting surface;

wherein said wavelength converter comprises:

a pre-formed porous matrix layer, the pre-formed porous matrix layer comprising pore structures; and

particles of a wavelength conversion material, wherein said particles of wavelength conversion material comprise non-agglomerated quantum dot particles, and at least a portion of the particles of wavelength conversion material are present within said pore structures.

11. The lighting device of claim 10, wherein:

the pre-formed porous matrix layer comprises particles of a matrix precursor material and a network of said pore structures; and

at least a portion of said particles of matrix precursor are sintered to one another to define at least a portion of said network of pore structures.

12. The lighting device of claim 10, wherein:

said pre-formed porous matrix layer is formed from a matrix precursor material; and

said pre-formed porous matrix layer has a density that is less than 90% of a theoretical density of said matrix precursor material.

13. The lighting device of claim 10, wherein said pre-formed porous matrix layer is formed from a matrix precursor material selected from the group consisting of aluminum oxide, an aluminosilicate, silicon dioxide, soda-lime silicate, sodium-borosilicate, lead-alkali silicate, titanium dioxide, yttrium aluminum garnet, lutetium aluminum garnet, zinc oxide, and zirconium oxide, and combinations thereof.
14. The lighting device of claim 10, wherein said quantum dot particles are selected from the group consisting of core quantum dots, core/shell quantum dots, quantum dot beads, and combinations thereof.
15. The lighting device of claim 10, wherein said particles of wavelength conversion material comprise particles of a first wavelength conversion material and particles of a second wavelength conversion material, wherein the first and second wavelength conversion materials differ from one another.
16. The lighting device of claim 10, wherein said particles of wavelength conversion material occupy from greater than or equal to about 10% to less than or equal to about 90% of said pore structures in said pre-formed porous matrix.
17. The lighting device of claim 10, wherein said pre-formed porous matrix layer is formed from a matrix material having a thermal conductivity greater than or equal to about 0.2 W/mK.
18. The light device of claim 10, wherein said particles of wavelength conversion material consist essentially of said non-agglomerated quantum dot particles.
19. A method of forming a wavelength converted light source, comprising:
forming a pre-formed matrix layer directly on a light emitting surface of a light source, the pre-formed porous matrix layer comprising pore structures; and
infiltrating particles of wavelength conversion material into said pre-formed porous matrix layer, such that at least a portion of the particles of wavelength conversion material are present within said pore structures;

wherein said particles of wavelength conversion materials comprise non-agglomerated quantum dot particles.

20. The method of claim 19, wherein forming said pre-formed matrix layer comprises:
applying a dispersion of particles of matrix precursor material in a first liquid phase to said light emitting surface to form a film;
removing the first liquid phase from said film to form a matrix precursor; and
heat treating said matrix precursor such that at least a portion of said particles of matrix precursor material bond to one another to form a network of said pore structures, thereby forming said pre-formed porous matrix layer.
21. The method of claim 19, wherein infiltrating said particles of wavelength conversion material into said pre-formed porous matrix layer comprises:
applying a dispersion of non-agglomerated particles of said wavelength conversion material in a second liquid phase onto a surface of said pre-formed porous matrix layer; and
executing a drying process to remove said second liquid phase.
22. The method of claim 19, wherein:
the pre-formed porous matrix layer comprises particles of a matrix precursor material and a network of said pore structures; and
the method further comprises sintering at least a portion of said particles of matrix precursor material to one another to define at least a portion of said pore structures.

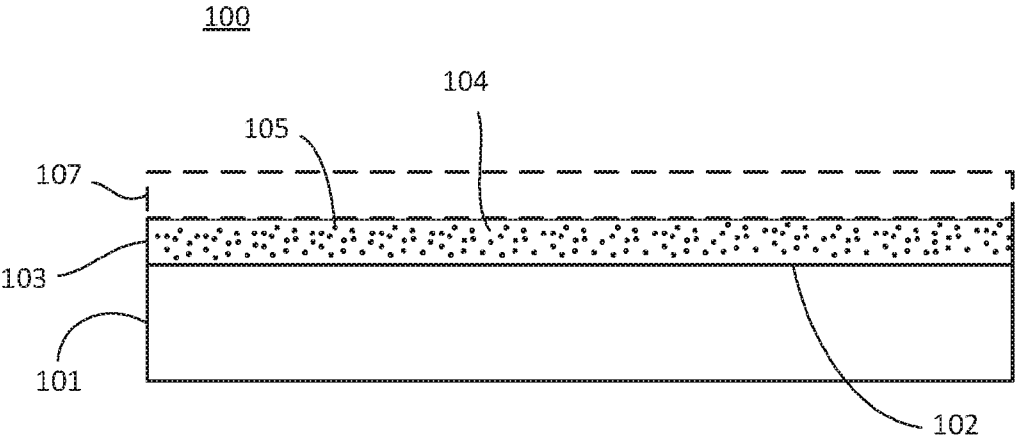


FIG. 1

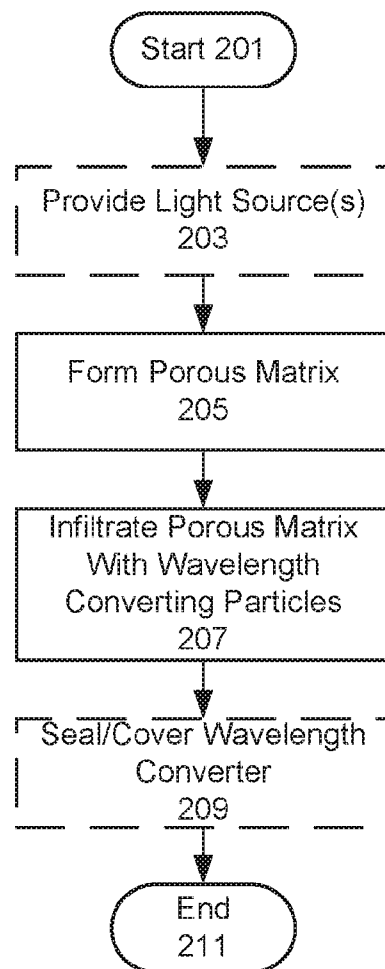
200

FIG. 2

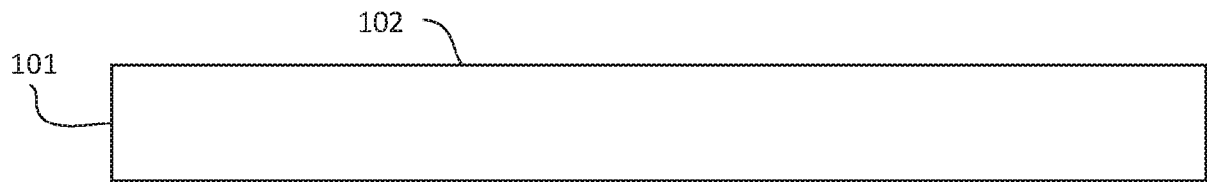


FIG. 3A

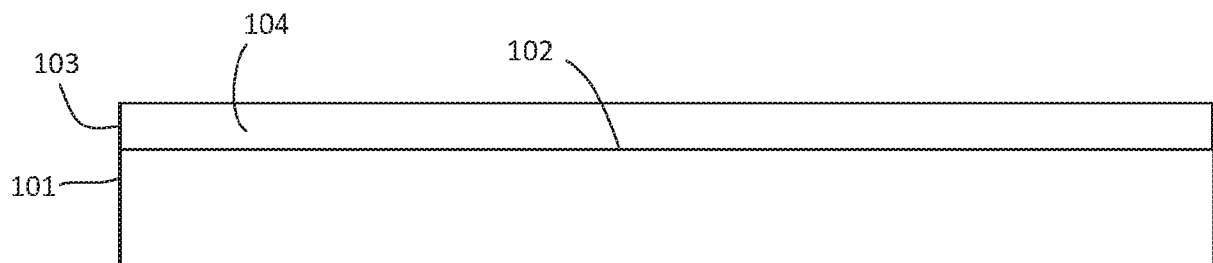


FIG. 3B

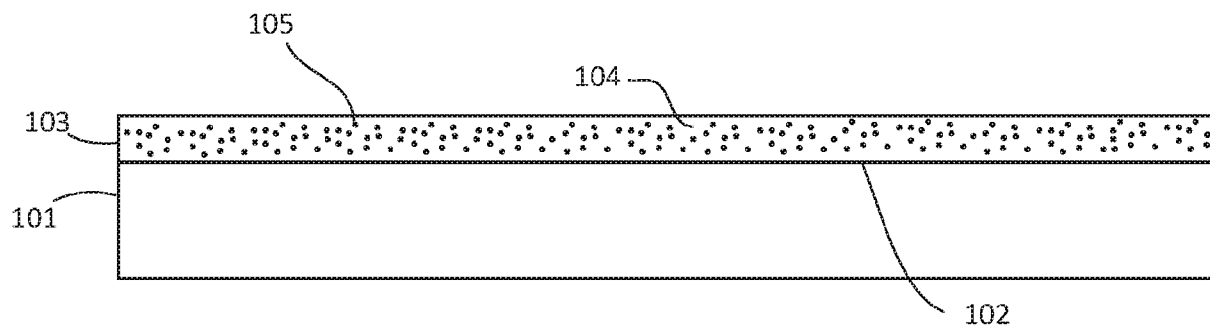


FIG. 3C

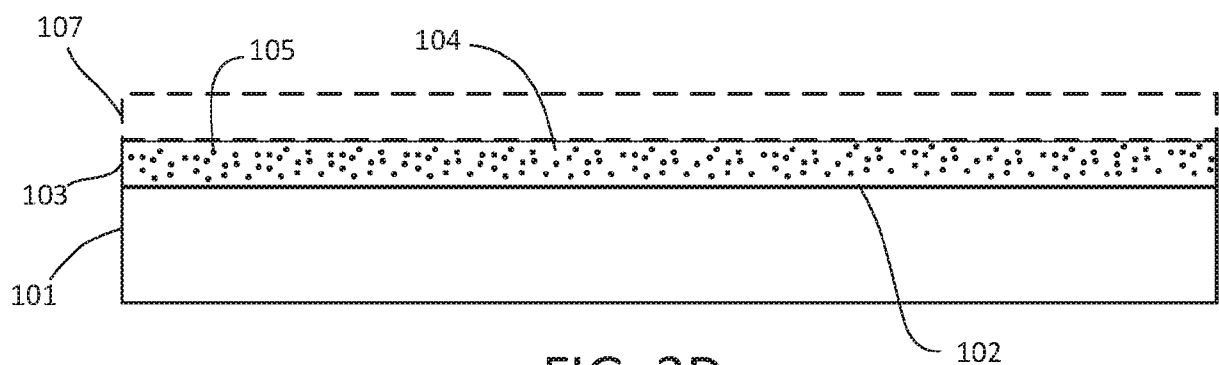


FIG. 3D

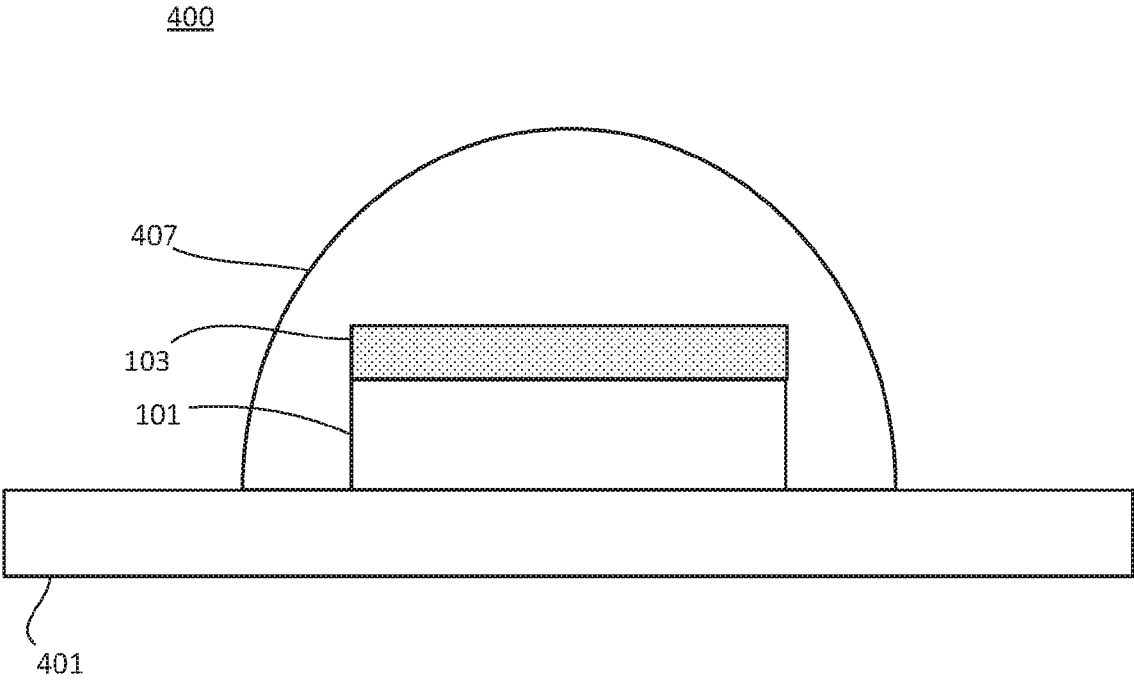


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2017/032676

A. CLASSIFICATION OF SUBJECT MATTER
 INV. H01L33/50
 ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 H01L C09K

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 practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 10 2014 101804 A1 (OSRAM OPTO SEMICONDUCTORS GMBH [DE]) 18 June 2015 (2015-06-18)	1-18
A	paragraphs [0001] - [0055]; figure 6 -----	20,22
X	WO 2010/077226 A1 (NANOSYS INC [US]; DUBROW ROBERT S [US]) 8 July 2010 (2010-07-08)	1,3-10, 12-18
	paragraphs [0001] - [0064]; figures 1, 2 -----	
X	US 2015/255688 A1 (STOLL ION [DE] ET AL) 10 September 2015 (2015-09-10)	10, 14-16,18
	paragraphs [0001] - [0087]; figures 5, 6, 7 -----	
X	US 2004/159849 A1 (NEGLEY GERALD H [US]) 19 August 2004 (2004-08-19)	1,2,4,5, 8-22
	the whole document -----	



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

25 July 2017

Date of mailing of the international search report

02/08/2017

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Saynova, Desislava

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2017/032676

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 102014101804 A1	18-06-2015	DE 102014101804 A1	18-06-2015
		DE 112014005953 A5	09-02-2017
		US 2016300985 A1	13-10-2016
		WO 2015091670 A1	25-06-2015

WO 2010077226 A1	08-07-2010	CN 102257599 A	23-11-2011
		EP 2370993 A1	05-10-2011
		JP 2012514071 A	21-06-2012
		KR 20110111391 A	11-10-2011
		WO 2010077226 A1	08-07-2010

US 2015255688 A1	10-09-2015	DE 102012110668 A1	08-05-2014
		DE 112013005312 A5	23-07-2015
		US 2015255688 A1	10-09-2015
		WO 2014072255 A1	15-05-2014

US 2004159849 A1	19-08-2004	AT 467235 T	15-05-2010
		CA 2515647 A1	02-09-2004
		CN 1748326 A	15-03-2006
		EP 1593165 A2	09-11-2005
		JP 4791351 B2	12-10-2011
		JP 2006518111 A	03-08-2006
		KR 20050105214 A	03-11-2005
		US 2004159849 A1	19-08-2004
		US 2004214358 A1	28-10-2004
		WO 2004075308 A2	02-09-2004
