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[Continued on next page]

(54) Title: REMOTE PHOSPHOR CONVERTED LED

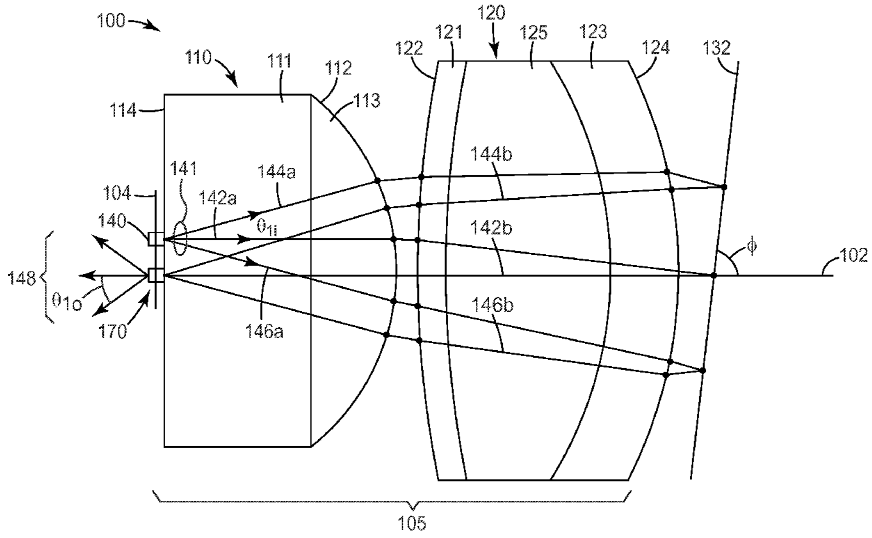

Fig. 1

(57) Abstract: The disclosure generally relates to broadband solid state illumination sources and image projectors that utilize a phosphor layer or material that is pumped or excited by light from one or more LEDs. The configuration is compact, efficient, and has especially low etendue.

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REMOTE PHOSPHOR CONVERTED LED

Related Applications

This application is related to the following U.S. Patent Applications, which are incorporated by reference: "REMOTE PHOSPHOR POLARIZATION CONVERTER" (Attorney Docket No. 67422US002), and "OPTICAL STRUCTURE FOR REMOTE PHOSPHOR" (Attorney Docket No. 67421US002), both filed on an even date herewith.

Technical Field

This disclosure relates generally to light sources, with particular application to solid state light sources that incorporate a light emitting diode (LED) and a phosphor. The disclosure also relates to associated articles, systems, and methods.

Background

Solid state light sources that emit broadband light are known. In some cases, such light sources are made by applying a layer of yellow-emitting phosphor onto a blue LED. As light from the blue LED passes through the phosphor layer, some of the blue light is absorbed, and a substantial portion of the absorbed energy is re-emitted by the phosphor as Stokes-shifted light at longer wavelengths in the visible spectrum, typically, yellow light. The phosphor thickness is small enough so that some of the blue LED light passes all the way through the phosphor layer, and combines with the yellow light from the phosphor to provide broadband output light having a white appearance.

Other LED-pumped phosphor light sources have also been proposed. In U.S. Patent 7,091,653 (Ouderkirk et al.), a light source is discussed in which ultraviolet (UV) light from an LED is reflected by a long-pass reflector onto a phosphor layer. The phosphor layer emits visible (preferably white) light, which light is substantially transmitted by the long-pass reflector. The LED, phosphor layer, and long-pass filter are arranged in such a way that as UV light travels from the LED to the long-pass reflector it does not pass through the phosphor layer.

Summary

The disclosure generally relates to broadband solid state illumination sources and image projectors that utilize a phosphor layer or material that is pumped or excited by light from one or more LEDs. The configuration is compact, efficient, and has especially low etendue. In one aspect, the present disclosure provides an illumination system that includes a light emitting diode

(LED) disposed on a substrate and configured to inject a first light beam along a first propagation direction through a collimating optic; a reflector disposed to reflect the first light beam back through the collimating optic; a phosphor disposed immediately adjacent the LED on a visible light transparent region of the substrate, the phosphor disposed to intercept the first light beam; wherein a major portion of the first light beam is downconverted by the phosphor to become a second light beam propagating through the visible light transparent region.

In another aspect, the present disclosure provides an image projector including an illumination system, a polarization converter capable of converting the second light beam to a third light beam having a first polarization direction, an imager disposed to intercept the first polarization direction of the second light beam, and projection optics. The illumination system includes a light emitting diode (LED) disposed on a substrate and configured to inject a first light beam along a first propagation direction through a collimating optic; a reflector disposed to reflect the first light beam back through the collimating optic; and a phosphor disposed immediately adjacent the LED on a visible light transparent region of the substrate, the phosphor disposed to intercept the first light beam. A major portion of the first light beam is downconverted by the phosphor to become a second light beam propagating through the visible light transparent region.

The above summary is not intended to describe each disclosed embodiment or every implementation of the present disclosure. The figures and the detailed description below more particularly exemplify illustrative embodiments.

Brief Description of the Drawings

Throughout the specification reference is made to the appended drawings, where like reference numerals designate like elements, and wherein:

FIG. 1 shows a cross-section schematic of an illumination system;

FIGS. 2A-2E show schematic views near the light output region of an illumination system; and

FIG. 3 shows a schematic diagram of an image projector.

The figures are not necessarily to scale. Like numbers used in the figures refer to like components. However, it will be understood that the use of a number to refer to a component in a given figure is not intended to limit the component in another figure labeled with the same number.

Detailed Description

The present application describes broadband solid state illumination sources that utilize a phosphor layer or material that is pumped or excited by light from one or more LEDs. The sources also include a reflector and collimating optics. In some cases, the reflector can be a dichroic reflector that reflects at least some of the LED light onto the layer of phosphor. The light exiting the LED propagates within a collimation angle that enters the collimating optic, which increases the illumination area with a subsequent decrease in the collimation angle of the light, resulting in a collimated light. The collimated light reflects from the reflector and is directed back through the collimating optic to the phosphor layer.

The present disclosure describes an LED that remotely illuminates a phosphor, where the LED is coupled to a collimation optic with a material having a relatively low index of refraction, and the phosphor is coupled to the collimation optic with a material having a relatively high index of refraction. In one particular embodiment, the LED and the phosphor may use a common collimation optic; however, separate collimation optics may also be used.

It is generally known that the etendue of a light source is proportional to the square of the refractive index of an encapsulant surrounding the source. Since many optical devices are etendue limited, it is usually preferred that the light source, for example an LED, is encapsulated in a low index material such as air. In some optical devices the LED is used to stimulate a wavelength converting material such as a phosphor or a semiconducting wavelength converter. Many phosphors and semiconducting wavelength converters are much more efficient when immersed in an encapsulant that has a relatively high refractive index. Also, semiconducting wavelength converters may be expensive, or contain hazardous materials, or both. In these cases, it may be desirable to immerse the wavelength converter in a higher index medium to reduce the area required. The disclosed devices have a high optical efficiency, with the LED in a low index encapsulant, and the phosphor in an encapsulant with a higher index, while not substantially increasing the etendue of the system.

In some cases, the LED emits blue light (or UV light), and the reflector reflects the blue LED light onto the phosphor layer. A portion of the blue LED light can combine with longer wavelength light emitted by the phosphor, to provide a broadband output beam, for example, light having a white appearance. In some cases, the LED and/or the phosphor can be disposed on a substrate, and the LED and phosphor are mounted or attached to the substrate immediately adjacent each other. In one particular embodiment, the substrate can be a flexible substrate or a rigid substrate, and can include a transparent region onto which the phosphor is deposited, as described elsewhere.

For purposes of the description provided herein, “color light” and “wavelength spectrum light” are both intended to mean light having a wavelength spectrum range which may be correlated to a specific color if visible to the human eye. The more general term “wavelength spectrum light” refers to both visible and other wavelength spectrums of light including, for example, infrared light.

In this regard, "light emitting diode" or "LED" refers to a diode that emits light, whether visible, ultraviolet, or infrared. It includes incoherent encased or encapsulated semiconductor devices marketed as "LEDs", whether of the conventional or super radiant variety. An "LED die" is an LED in its most basic form, that is, in the form of an individual component or chip made by semiconductor processing procedures.

In some cases, the LED can be a short-wavelength LED capable of emitting UV photons. In general, the LED may be composed of any suitable materials, such as organic semiconductors or inorganic semiconductors, including Group IV elements such as Si or Ge; III-V compounds such as InAs, AlAs, GaAs, InP, AlP, GaP, InSb, AlSb, GaSb, GaN, AlN, InN and alloys of III-V compounds such as AlGaInP and AlGaInN; II-VI compounds such as ZnSe, CdSe, BeSe, MgSe, ZnTe, CdTe, BeTe, MgTe, ZnS, CdS, BeS, MgS and alloys of II-VI compounds, or alloys of any of the compounds listed above.

In some cases, the LED can include one or more p-type and/or n-type semiconductor layers, one or more active layers that may include one or more potential and/or quantum wells, buffer layers, substrate layers, and superstrate layers.

In some cases, the LED can include CdMgZnSe alloys having compounds ZnSe, CdSe, and MgSe as the three constituents of the alloy. In some cases, one or more of Cd, Mg, and Zn, especially Mg, may have zero concentration in the alloy and therefore, may be absent from the alloy. For example, the LCD can further include a light converting element (LCE) that can be used to convert light from one wavelength to another. In some cases, the LCE can include a Cd0.70Zn0.30Se quantum well capable of emitting in the red, or a Cd0.33Zn0.67Se quantum well capable of emitting in the green. As another example, the LED and/or the LCE can include an alloy of Cd, Zn, Se, and optionally Mg, in which case, the alloy system can be represented by Cd(Mg)ZnSe. As another example, the LED and/or the LCE can include an alloy of Cd, Mg, Se, and optionally Zn. In some cases, a quantum well LCE has a thickness in a range from about 1 nm to about 100 nm, or from about 2 nm to about 35 nm.

In some cases, a semiconductor LED or LCE may be n-doped or p-doped where the doping can be accomplished by any suitable method and by inclusion of any suitable dopant. In some cases, the LED and the LCE are from the same semiconductor group. In some cases, the

LED and the LCE are from two different semiconductor groups. For example, in some cases, the LED is a III-V semiconductor device and the LCE is a II-VI semiconductor device. In some cases, the LEDs include AlGaInN semiconductor alloys and the LCEs include Cd(Mg)ZnSe semiconductor alloys. The LCE may generally be a phosphor such as a phosphor particle in a organic binder, in an inorganic binder, or may be semiconductors such as ZnSe or ZnS compounds.

An LCE can be disposed on or attached to a corresponding electroluminescent element by any suitable method such as by an adhesive such as a hot melt adhesive, welding, pressure, heat or any combinations of such methods. Examples of suitable hot melt adhesives include semicrystalline polyolefins, thermoplastic polyesters, and acrylic resins.

In one particular embodiment, the LED die may be formed from a combination of one or more Group III elements and of one or more Group V elements (III-V semiconductor). Examples of suitable III-V semiconductor materials include nitrides, such as gallium nitride, and phosphides, such as indium gallium phosphide. Other types of III-V materials can also be used, as well as inorganic materials from other groups of the periodic table. The component or chip can include electrical contacts suitable for application of power to energize the device. Examples include wire bonding, tape automated bonding (TAB), or flip-chip bonding. The individual layers and other functional elements of the component or chip are typically formed on the wafer scale, and the finished wafer can then be diced into individual piece parts to yield a multiplicity of LED dies. The LED die may be configured for surface mount, chip-on-board, or other known mounting configurations. Some packaged LEDs are made by forming a polymer encapsulant over an LED die and an associated reflector cup. An "LED" for purposes of this application should also be considered to include organic light emitting diodes, commonly referred to as OLEDs.

In one particular embodiment, the phosphor may be a semiconductor such as II-VI based systems, or phosphors based on nitrides, sulfides, selenides, and aluminum oxides, as described elsewhere. The phosphor may be a broad emitter, including one or more wavelength ranges covering the red, green, or blue spectrum, or it may have a medium bandwidth, covering for example the green portion of the spectrum, or it may be a narrow-band emitter. In some cases, the phosphor layer may be optically thin, meaning that it transmits between 5 and 50% of the excitation wavelength, or more preferably, between 5 and 30% of the light. In some cases, the phosphor layer can include more than one type of phosphor so that the downconverted light includes more than one wavelength of light.

The present disclosure allows etendue matching of an LED source that does not require encapsulation for good efficiency. In some cases, the LED source can be encapsulated in a material having an index of refraction between about 1.0 and about 1.2, or approximately 1.0 (that is, air). In some cases, the LED source may have a limitation in the permissible drive current density. In some cases, a phosphor can operate at a high power density, and for higher efficiency of the pumped system is generally preferred to optically couple the phosphor to a primary optic using an encapsulant.

In one particular embodiment, the area of the LED source is significantly larger than the area of the phosphor, and a focusing optic can be used to increase the angular range illuminating the phosphor, which can be coupled to a focusing optic with an encapsulant having a higher refractive index than the refractive index of the material surrounding the LED. In some cases, the encapsulant can have an index of refraction between about 1.2 and about 1.6, or between about 1.4 and about 1.5, or, for example, about a 1.41 refractive index.

In some cases, the etendue of the encapsulated phosphor can be matched with an unencapsulated LED, for example, by concentrating the light from the LED source onto the phosphor by using a tapered rod. The tapered rod may be optically coupled to the collimating optic, or may be separated by an air gap. The phosphor can be optically coupled to the narrower base of the tapered rod with an encapsulant material such as dimethyl silicone. In some cases, a Compound Parabolic Concentrator (CPC) can be used in place of the tapered rod. The CPC or tapered rod may be made from glass or plastic. The phosphor may be bonded to the tapered rod or CPC with a material having a refractive index of about 1.2 or higher, preferably 1.4 or higher, such as, for example, dimethyl silicone.

FIG. 1 shows a cross-section schematic of an illumination system 100 according to one aspect of the disclosure. In FIG. 1, the illumination system 100 includes a light collection optic 105 including a first lens element 110 and a second lens element 120. The light collection optic 105 includes a light input surface 114 and an optical axis 102 perpendicular to the light input surface 114. A first light source 140 is disposed on a light injection surface 104 that faces the light input surface 114. A light output region 170 is disposed immediately adjacent the first light source 140 on the light injection surface 104. In some cases, one of the light output region 170 and the first light source 140 is disposed on the optical axis 102 and immediately adjacent each other. In some cases, the light output region 170 and the first light source 140 are each displaced from the optical axis 102, immediately adjacent each other. Generally, however, the first light source 140 and the light output region 170 are disposed in close proximity to the optical axis 102, so that the collimation angles of the light emitted from the first light source 140 and directed through to the light output region 170 can be maintained. FIG. 1 shows an arrangement of first light source 140 slightly above the optical axis 102, and the light output region 170 disposed on the optical axis

102. In some cases, a second light source (not shown) can be disposed at a position removed from light injection surface 104, to direct a second light directly toward the light conversion region 170.

Any suitable substrate can be used for light injection surface 104, and may include conductive layers or traces to carry electrical power to the LED. The substrate also preferably has a relatively high heat conduction and relatively low thermal resistance in order to effectively carry heat away from the LED and/or phosphor layer so as to maintain lower operating temperatures thereof. To promote such lower operating temperatures, the substrate may include or be thermally coupled to a suitable heat sink, for example, a relatively thick layer of copper, aluminum, or other suitable metal or other thermally conductive material (not shown). In some cases the substrate may be or comprise a highly reflective surface such as a metal mirror, a metal mirror with dielectric coatings to enhance reflectivity, or a diffusely reflective surface such as microvoided polyester or titania filled polymer, or a multilayer optical film such as 3M™ Vikuiti™ Enhanced Specular Reflector (ESR) film. The substrate may also be or comprise any of the substrates discussed elsewhere herein.

The substrate can include a dielectric layer. Suitable dielectric layers include polyesters, polycarbonates, liquid crystal polymers, and polyimides. Suitable polyimides include those available under the trade names KAPTON, available from DuPont; APICAL, available from Kaneka Texas corporation; SKC Kolon PI, available from SKC Kolon PI Inc.; and UPILEX and UPISEL, available from Ube Industries. Polyimides available under the trade designations UPILEX S, UPILEX SN, and UPISEL VT, all available from Ube Industries, Japan, are particularly advantageous in many applications. These polyimides are made from monomers such as biphenyl tetracarboxylic dianhydride (BPDA) and phenyl diamine (PDA).

Additional design details of exemplary flexible substrates suitable for use in the disclosed embodiments can be found in the following commonly owned U.S. patent applications: U.S. application 61/409,796, “Flexible LED Device and Method of Making”, filed Nov. 3, 2010 (Attorney Docket 66938US003); U.S. application 61/409,801, “Flexible LED Device for Thermal Management and Method of Making”, filed Nov. 3, 2010 (Attorney Docket 67018US002); U.S. application 61/428034, “Remote Phosphor LED Constructions”, filed Dec. 29, 2010 (Attorney Docket 67006US002); and U.S. application 61/428038, “LED Color Combiner”, filed Dec. 29, 2010 (Attorney Docket 67010US002).

In one particular embodiment, illumination system 100 further includes a reflector 132 disposed facing the light collection optics 105 along the optical axis 102, such that the first lens element 110 and the second lens element 120 are between the reflector 132 and the light input surface 114. The reflector 132 can be disposed at a tilt angle φ to the optical axis, and can be a dichroic reflector capable of reflecting the first color light 141 and transmitting all other colors of light. Reflector 132 can instead be a broadband reflector such as a broadband mirror.

In one particular embodiment, light collection optics 105 can be a light collimation optic 105 that serves to collimate the light emitted from the first light source 140. Light collimation optics 105 can include a one lens light collimator (not shown), a two lens light collimator (shown), a diffractive optical element (not shown), or a combination thereof. The two lens light collimator has first lens element 110 that includes a first convex surface 112 disposed opposite the light input surface 114. Second lens element 120 includes a second surface 122 facing the first convex surface 112, and a third convex surface 124 opposite the second surface 122. Second surface 122 can be selected from a convex surface, a planar surface, and a concave surface.

The path of the first color light 141 from first light source 140 can be traced through illumination system 100. First color light 141 includes a first central light ray 142a travelling in the first light propagation direction, and a cone of rays within first input light collimation angle θ1i, the boundaries of which are represented by first boundary light rays 144a, 146a. The first central light ray 142a is injected from first light source 140 into light input surface 114 in a direction generally parallel to the optical axis 102, passes through first lens element 110, second lens element 120, and reflects from reflector 132 such that the first central reflected light ray 142b is coincident with the optical axis 102 as shown in FIG. 1. Each of the first boundary light rays 144a, 146a, are injected into the light input surface 114 in a direction generally at the first input light collimation angle θ1i to the optical axis 102, pass through first lens element 110, second lens element 120, and reflects from reflector 132 such that the first boundary reflected light rays 144b, 146b, respectively, are generally parallel to the optical axis 102 as shown, before re-entering light collimation optics 105. As can be seen from FIG. 1, the light collimation optics 105 serve to collimate the first color light 141 passing from the first light source 140 to the reflector 132.

Each of the first central light ray 142a and the first boundary light rays 144a, 146a, reflect from the reflector 132 and travel back through the light collimation optics 105 as collimated light rays essentially parallel to, and in some cases centered upon (for example, as shown in FIG. 1), the optical axis 102. In one particular embodiment as shown in FIG. 1, the collimated light rays converge to exit the illumination system 100 through the light output region 170 as a first output light rays 148 having a first output collimation angle θ1o.

In one particular embodiment, the input collimation angles θ1i can be the same as the output collimation angle θ1o, and injection optics (not shown) associated with the first light source 140 can restrict these input collimation angles to angles between about 10 degrees and about 80 degrees, or between about 10 degrees to about 70 degrees, or between about 10 degrees to about

60 degrees, or between about 10 degrees to about 50 degrees, or between about 10 degrees to about 40 degrees, or between about 10 degrees to about 30 degrees or less. In some cases, the light collimation optics 105 and the reflector 132 can be fabricated such that the output collimation angle θ1o can be the same, and also substantially equal to the input collimation angle θ1i. In one particular embodiment, each of the input collimation angle ranges from about 60 to about 70 degrees, and the output collimation angles also ranges from about 60 to about 70 degrees.

FIG. 2A shows a schematic view near the light output region 170 of the illumination system 100 shown in FIG. 1, according to one aspect of the disclosure. Each of the elements 104-170 shown in FIG. 2A correspond to like-numbered elements shown in FIG. 1, which have been described previously. In FIG. 2A, the light output region 170 includes a phosphor 150 disposed on a visibly transparent region 106 of light injection surface 104 surrounded by an encapsulant 155. Encapsulant 155 has an index of refraction greater than the index of refraction of the material surrounding the first light source 140, as described elsewhere. Encapsulant 155 can be any of the encapsulating materials described previously, such as, for example, dimethyl silicone. In some cases, encapsulant 155 can completely fill the separation between the light injection surface 104 and the light input surface 114. In some cases, encapsulant 155 can instead be fabricated as a lens that includes a curved surface 156 (as shown in FIG. 2A), to focus the reflected light rays 142b, 144b, 146b that exit light input surface 114 onto the phosphor 150. Upon intercepting phosphor 150, a major portion of reflected light rays 142b, 144b, 146b are wavelength downconverted to exit illumination system 100 as output light rays 148 having the output collimation angle θ1o.

FIG. 2B shows a schematic view near the light output region 170 of the illumination system 100 shown in FIG. 1, according to one aspect of the disclosure. Each of the elements 104-170 shown in FIG. 2B correspond to like-numbered elements shown in FIG. 2A, which have been described previously. In FIG. 2B, the light output region 170 further includes a tapered rod 107 disposed adjacent the visibly transparent region 106. Tapered rod 107 can be any of the tapered rods described elsewhere, and may have reflective surfaces or polished surfaces to enable TIR from the surfaces. Tapered rod 107 is configured to transport and further concentrate output light rays 148 such they exit illumination system 100 having the second output collimation angle θ2o. In some cases, second output collimation angle θ2o may be the same as input collimation angle θ1i.

FIG. 2C shows a schematic view near the light output region 170 of the illumination system 100 shown in FIG. 1, according to one aspect of the disclosure. Each of the elements 104-170 shown in FIG. 2C correspond to like-numbered elements shown in FIG. 2A, which have been described previously. In FIG. 2C, the light output region 170 further includes a CPC 108 disposed adjacent the visibly transparent region 106. CPC 108 can be any of the CPCs described elsewhere, and may have reflective surfaces or polished surfaces to enable TIR from the surfaces. CPC 108 is configured to transport and further concentrate output light rays 148 such they exit illumination system 100 having the third output collimation angle θ3o. In some cases, third output collimation angle θ3o may be the same as input collimation angle θ1i.

FIG. 2D shows a schematic view near the light output region 170 of the illumination system 100 shown in FIG. 1, according to one aspect of the disclosure. Each of the elements 104-170 shown in FIG. 2D correspond to like-numbered elements shown in FIG. 1, which have been described previously. In FIG. 2D, the light output region 170 includes a phosphor 150 surrounded by an encapsulant 155 disposed, on a visibly transparent region 106 of light injection surface 104. Encapsulant 155 has an index of refraction greater than the index of refraction of the material surrounding the first light source 140, as described elsewhere. Encapsulant 155 can be any of the encapsulating materials described previously, such as, for example, dimethyl silicone. Encapsulant 155 is in the form of a tapered rod 107 disposed adjacent the visibly transparent region 106, and the phosphor 150 is disposed at the narrow end of tapered rod 107. Tapered rod 107 can be any of the tapered rods described elsewhere, and may have reflective surfaces or polished surfaces to enable TIR from the surfaces. Tapered rod 107 is configured to transport and further concentrate reflected light rays 142b, 144b, 146b, such they exit illumination system 100 as output light rays 148 having the fourth output collimation angle θ4o. In some cases, fourth output collimation angle θ4o may be the same as input collimation angle θ1i.

FIG. 2E shows a schematic view near the light output region 170 of the illumination system 100 shown in FIG. 1, according to one aspect of the disclosure. Each of the elements 104-170 shown in FIG. 2E correspond to like-numbered elements shown in FIG. 1, which have been described previously. In FIG. 2E, the light output region 170 includes a phosphor 150 surrounded by an encapsulant 155 disposed, on a visibly transparent region 106 of light injection surface 104. Encapsulant 155 has an index of refraction greater than the index of refraction of the material surrounding the first light source 140, as described elsewhere. Encapsulant 155 can be any of the encapsulating materials described previously, such as, for example, dimethyl silicone. Encapsulant 155 is in the form of a CPC 108 disposed adjacent the visibly transparent region 106, and the phosphor 150 is disposed at the narrow end of CPC 108. CPC 108 can be any of the CPCs described elsewhere, and may have reflective surfaces or polished surfaces to enable TIR from the surfaces. CPC 108 is configured to transport and further concentrate reflected light rays 142b, 144b, 146b, such they exit illumination system 100 as output light rays 148 having the fifth output collimation angle θ5o. In some cases, fifth output collimation angle θ5o may be the same as input collimation angle θ1i.

FIG. 3 shows a schematic diagram of an image projector 1, according to one aspect of the disclosure. Image projector 1 includes an illuminator module 10 that is capable of injecting a partially collimated light output 24 into an optional homogenizing polarization converter module 30 where the partially collimated light output 24 becomes converted to a homogenized polarized light 45 that exits the optional homogenizing polarization converter module 30 and enters an image generator module 50. The image generator module 50 outputs an imaged light 65 that enters a projection module 70 where the imaged light 65 becomes a projected imaged light 80.

In one aspect, illuminator module 10 includes an input light source that is input through a light collimation optics 105 in illumination system 100, as described elsewhere. The illumination system 100 produces a light output that exits illuminator module 10 as partially collimated light output 24, as described elsewhere.

In one aspect, the input light source is unpolarized, and the partially collimated light output 24 is also unpolarized. The partially collimated light output 24 can be a polychromatic combined light that comprises more than one wavelength spectrum of light. For purposes of the description provided herein, “color light” and “wavelength spectrum light” are both intended to mean light having a wavelength spectrum range which may be correlated to a specific color if visible to the human eye. The more general term “wavelength spectrum light” refers to both visible and other wavelength spectrums of light including, for example, infrared light.

According to one aspect, each input light source comprises one or more light emitting diodes (LED’s). Various light sources can be used such as lasers, laser diodes, organic LED's (OLED's), and non solid state light sources such as ultra high pressure (UHP), halogen or xenon lamps with appropriate collectors or reflectors. Light sources, light collimators, lenses, and light integrators useful in the present invention are further described, for example, in Published U.S. Patent Application No. US 2008/0285129, the disclosure of which is herein included in its entirety.

In one aspect, optional homogenizing polarization converter module 30 includes a polarization converter 40 that is capable of converting unpolarized partially collimated light output 24 into homogenized polarized light 45. Optional homogenizing polarization converter module 30 further can include a monolithic array of lenses 42, such as a optional monolithic FEA of lenses described elsewhere that can homogenize and improve the uniformity of the partially collimated combined color light output 24 that exits the optional homogenizing polarization converter module 30 as homogenized polarized light 45. Representative arrangements of optional FEA associated with the optional homogenizing polarization converter module 30 are described, for example, in co-pending U.S. Patent Serial Nos. 61/346183 entitled FLY EYE INTEGRATOR POLARIZATION CONVERTER (Attorney Docket No. 66247US002, filed May 19, 2010); 61/346190 entitled POLARIZED PROJECTION ILLUMINATOR (Attorney Docket No. 66249US002, filed May 19, 2010); and 61/346193 entitled COMPACT ILLUMINATOR (Attorney Docket No. 66360US002, filed May 19, 2010).

In one aspect, image generator module 50 includes a polarizing beam splitter (PBS) 56, representative imaging optics 52, 54, and a spatial light modulator 58 that cooperate to convert the homogenized polarized light 45 into an imaged light 65. Suitable spatial light modulators (that is, image generators) have been described previously, for example, in U.S. Patent Nos. 7,362,507 (Duncan et al.), 7,529,029 (Duncan et al.); in U.S. Publication No. 2008-0285129-A1 (Magarill et al.); and also in PCT Publication No. WO2007/016015 (Duncan et al.). In one particular embodiment, homogenized polarized light 45 is a divergent light originating from each lens of the optional FEA. After passing through imaging optics 52, 54 and PBS 56, homogenized polarized light 45 becomes imaging light 60 that uniformly illuminates the spatial light modulator. In one particular embodiment, each of the divergent light ray bundles from each of the lenses in the optional FEA illuminates a major portion of the spatial light modulator 58 so that the individual divergent ray bundles overlap each other.

In one aspect, projection module 70 includes representative projection optics 72, 74, 76, that can be used to project imaged light 65 as projected light 80. Suitable projection optics 72, 74, 76 have been described previously, and are well known to those of skill in the art.

Following are a list of embodiments of the present disclosure.

Item 1 is an illumination system, comprising: a light emitting diode (LED) disposed on a substrate and configured to inject a first light beam along a first propagation direction through a collimating optic; a reflector disposed to reflect the first light beam back through the collimating optic; an encapsulated phosphor disposed immediately adjacent the LED on a visible light transparent region of the substrate, the encapsulated phosphor disposed to intercept the first light beam; wherein a major portion of the first light beam is downconverted by the encapsulated phosphor to become a second light beam propagating through the visible light transparent region.

Item 2 is the illumination system of item 1, wherein the phosphor comprises an encapsulated phosphor.

Item 3 is the illumination system of item 1, wherein the encapsulated phosphor comprises an encapsulant having an index of refraction between about 1.2 and about 1.6.

Item 4 is the illumination system of item 2 or item 3, wherein the encapsulated phosphor comprises an encapsulant having an index of refraction between about 1.4 and about 1.5.

Item 5 is the illumination system of item 1 to item 4, further comprising a low-index material having an index of refraction between about 1.0 and about 1.2 between the LED and the collimating optic.

Item 6 is the illumination system of item 5, wherein the low index material is air.

Item 7 is the illumination system of item 1 to item 6, wherein the first light beam comprises first light rays propagating within a first collimation angle of the first propagation direction.

Item 8 is the illumination system of item 1 to item 7, wherein the second light beam comprises second light rays propagating within a second collimation angle of a second propagation direction opposite the first propagation direction.

Item 9 is the illumination system of item 1 to item 8, further comprising a focusing optical element disposed between the encapsulated phosphor and the collimating optic, the focusing optical element capable of concentrating the first light beam.

Item 10 is the illumination system of item 9, wherein the focusing optical element comprises a tapered glass rod or a Compound Parabolic Concentrator (CPC).

Item 11 is the illumination system of item 1 to item 10, wherein the phosphor comprises dimethyl silicone encapsulant.

Item 12 is the illumination system of item 1 to item 11, wherein the collimating optic comprises an optical axis and at most one of the LED or the encapsulated phosphor are disposed on the optical axis.

Item 13 is the illumination system of item 1 to item 12, wherein the reflector is a broadband reflector.

Item 14 is the illumination system of item 1 to item 13, further comprising a second LED disposed to inject a third light beam directly toward the phosphor.

Item 15 is an image projector, comprising: an illumination system, comprising: a light emitting diode (LED) disposed on a substrate and configured to inject a first light beam along a first propagation direction through a collimating optic; a reflector disposed to reflect the first light beam back through the collimating optic; a phosphor disposed immediately adjacent the LED on a visible light transparent region of the substrate, the phosphor disposed to intercept the first light beam; wherein a major portion of the first light beam is downconverted by the phosphor to become a second light beam propagating through the visible light transparent region; a polarization converter capable of converting the second light beam to a third light beam having a first polarization direction; an imager disposed to intercept the first polarization direction of the second light beam; and projection optics.

Unless otherwise indicated, all numbers expressing feature sizes, amounts, and physical properties used in the specification and claims are to be understood as being modified by the term "about." Accordingly, unless indicated to the contrary, the numerical parameters set forth in the foregoing specification and attached claims are approximations that can vary depending upon the desired properties sought to be obtained by those skilled in the art utilizing the teachings disclosed herein.

All references and publications cited herein are expressly incorporated herein by reference in their entirety into this disclosure, except to the extent they may directly contradict this disclosure. Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a variety of alternate and/or equivalent implementations can be substituted for the specific embodiments shown and described without departing from the scope of the present disclosure. This application is intended to cover any adaptations or variations of the specific embodiments discussed herein. Therefore, it is intended that this disclosure be limited only by the claims and the equivalents thereof.

What is claimed is:

1. An illumination system, comprising:

   a light emitting diode (LED) disposed on a substrate and configured to inject a first light beam along a first propagation direction through a collimating optic;

   a reflector disposed to reflect the first light beam back through the collimating optic;

   a phosphor disposed immediately adjacent the LED on a visible light transparent region of the substrate, the phosphor disposed to intercept the first light beam;

   wherein a major portion of the first light beam is downconverted by the phosphor to become a second light beam propagating through the visible light transparent region.

2. The illumination system of claim 1, wherein the phosphor comprises an encapsulated phosphor.

3. The illumination system of claim 2, wherein the encapsulated phosphor comprises an encapsulant having an index of refraction between about 1.2 and about 1.6.

4. The illumination system of claim 2, wherein the encapsulated phosphor comprises an encapsulant having an index of refraction between about 1.4 and about 1.5.

5. The illumination system of claim 1, further comprising a low-index material having an index of refraction between about 1.0 and about 1.2 between the LED and the collimating optic.

6. The illumination system of claim 5, wherein the low-index material is air.

7. The illumination system of claim 1, wherein the first light beam comprises first light rays propagating within a first collimation angle of the first propagation direction.

8. The illumination system of claim 1, wherein the second light beam comprises second light rays propagating within a second collimation angle of a second propagation direction opposite the first propagation direction.

9. The illumination system of claim 1, further comprising a focusing optical element disposed between the phosphor and the collimating optic, the focusing optical element capable of concentrating the first light beam.

10. The illumination system of claim 9, wherein the focusing optical element comprises a tapered glass rod or a Compound Parabolic Concentrator (CPC).

11. The illumination system of claim 1, wherein the phosphor comprises a dimethyl silicone encapsulant.

12. The illumination system of claim 1, wherein the collimating optic comprises an optical axis and at most one of the LED or the phosphor are disposed on the optical axis.

13. The illumination system of claim 1, wherein the reflector is a broadband reflector.

14. The illumination system of claim 1, further comprising a second LED disposed to inject a third light beam directly toward the phosphor.

15. An image projector, comprising:

an illumination system, comprising:

a light emitting diode (LED) disposed on a substrate and configured to inject a first light beam along a first propagation direction through a collimating optic;

a reflector disposed to reflect the first light beam back through the collimating optic;

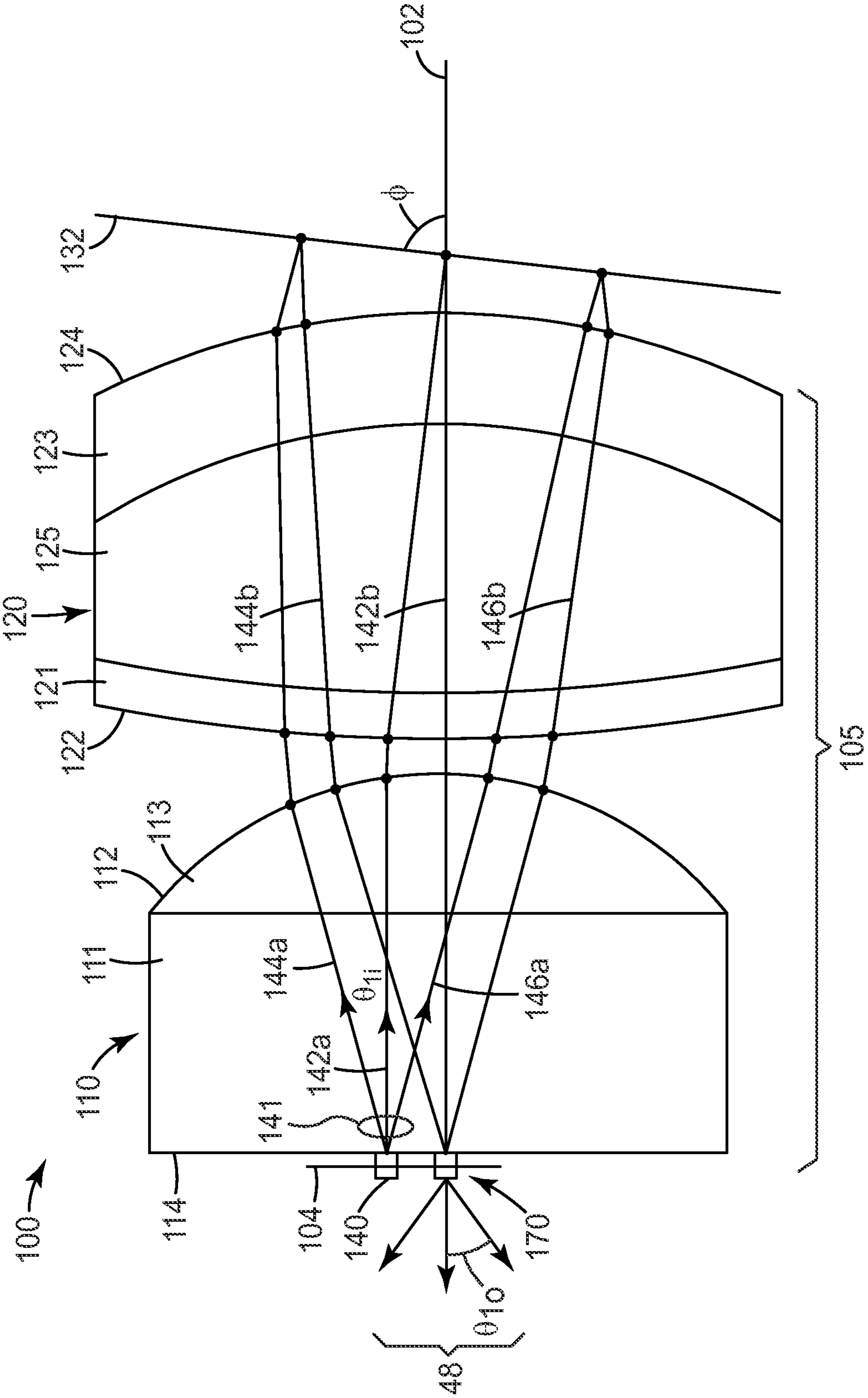
a phosphor disposed immediately adjacent the LED on a visible light transparent region of the substrate, the phosphor disposed to intercept the first light beam;

wherein a major portion of the first light beam is downconverted by the phosphor to become a second light beam propagating through the visible light transparent region;

a polarization converter capable of converting the second light beam to a third light beam having a first polarization direction;

an imager disposed to intercept the first polarization direction of the second light beam; and

projection optics.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148
170
ϕ
θ_{1i}
θ_{1o}

Fig. 1

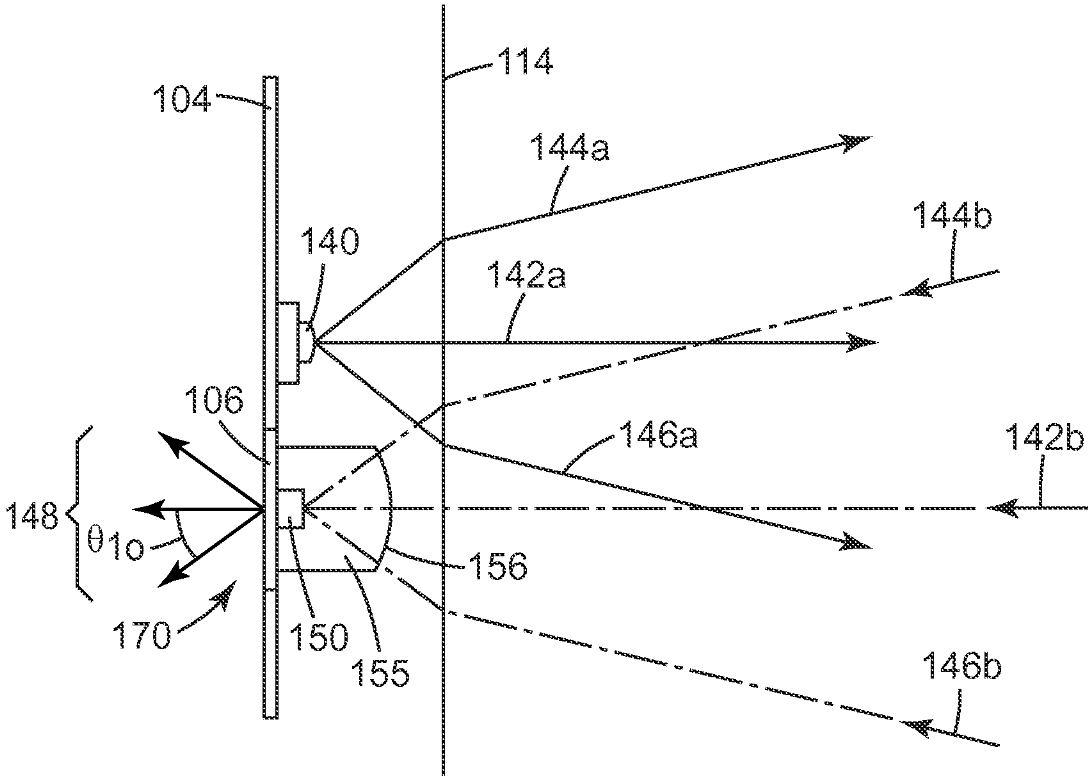
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Fig. 2A

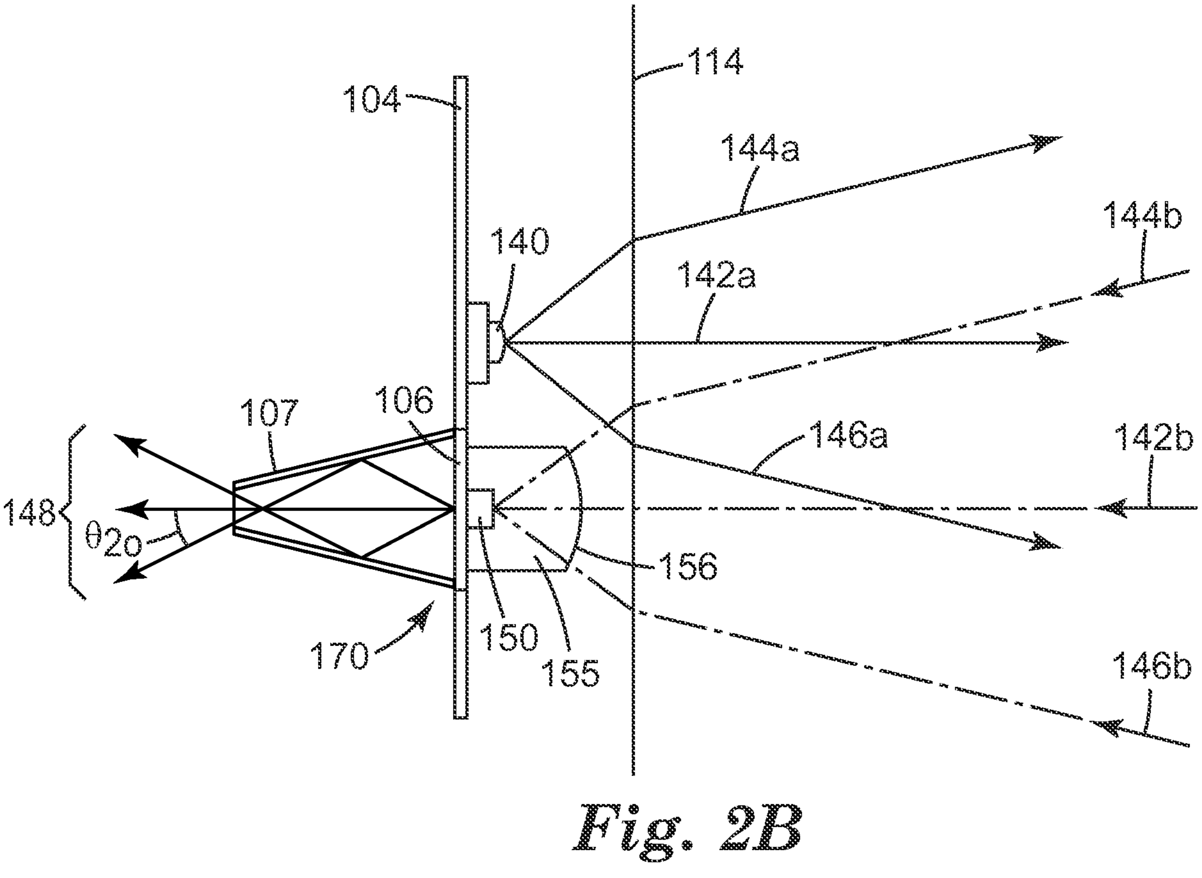
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Fig. 2B

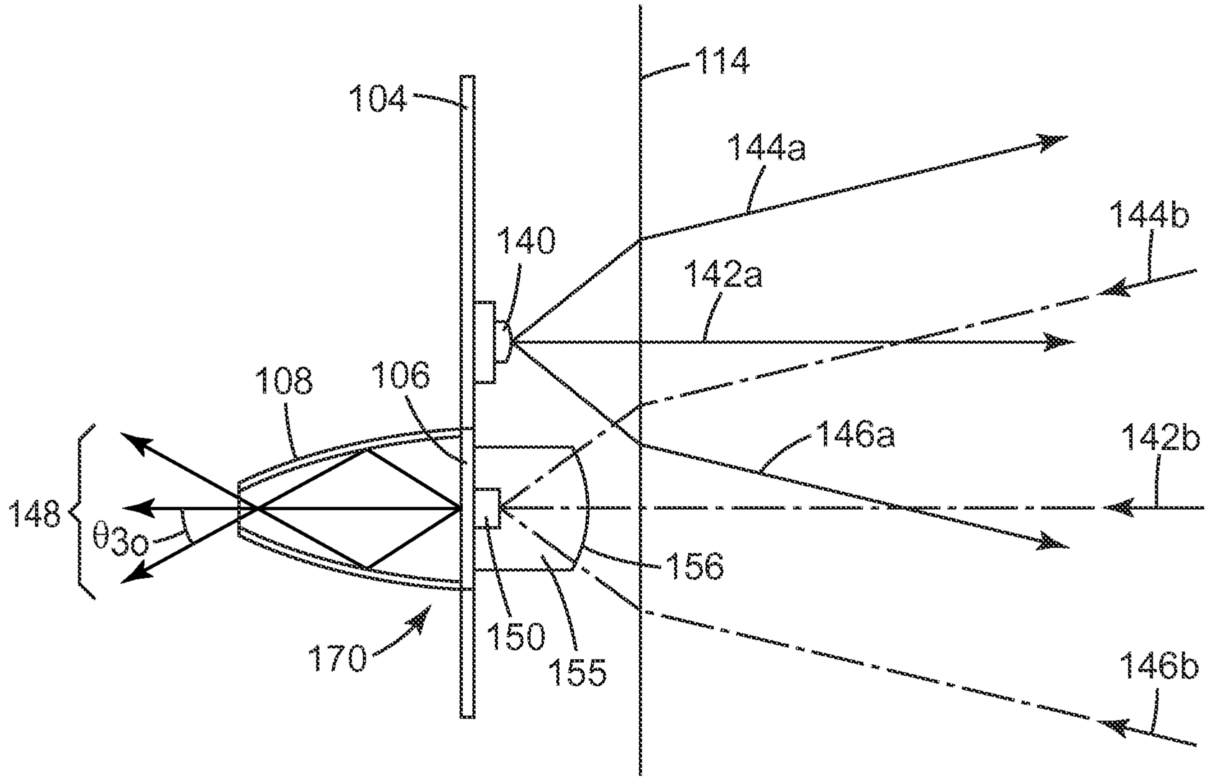
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Fig. 2C

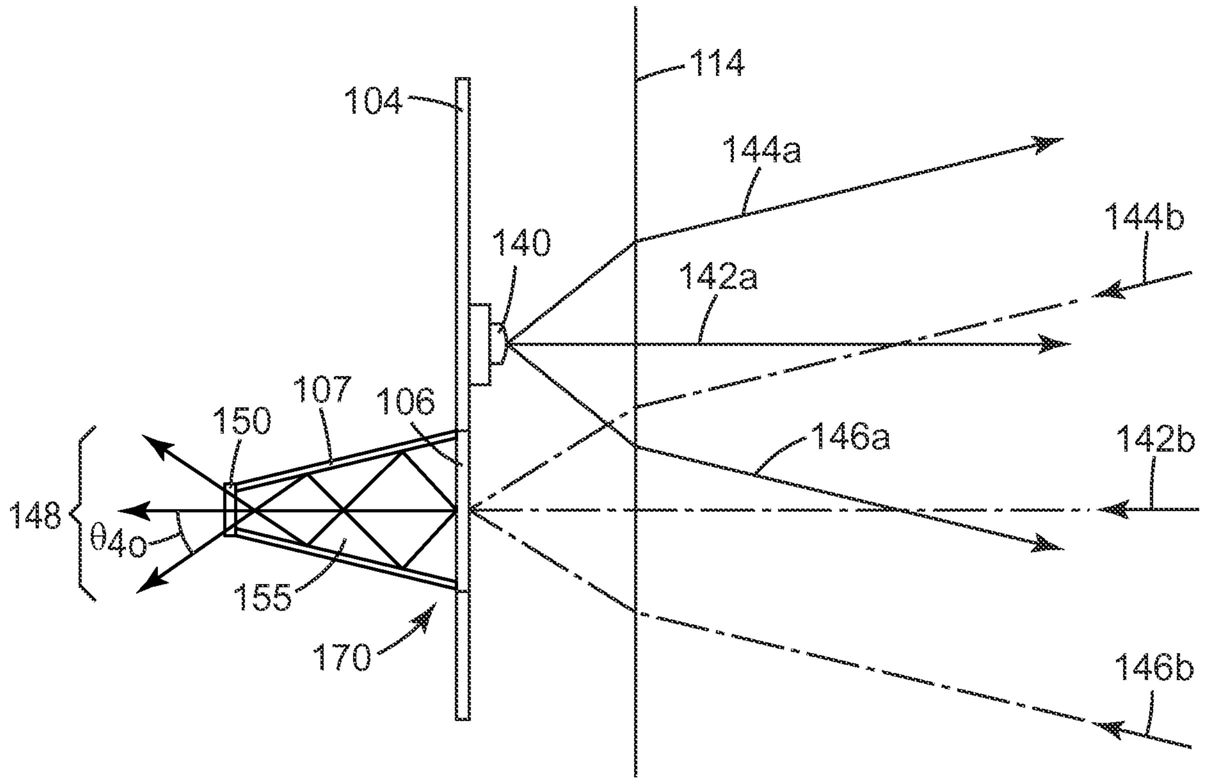
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Fig. 2D

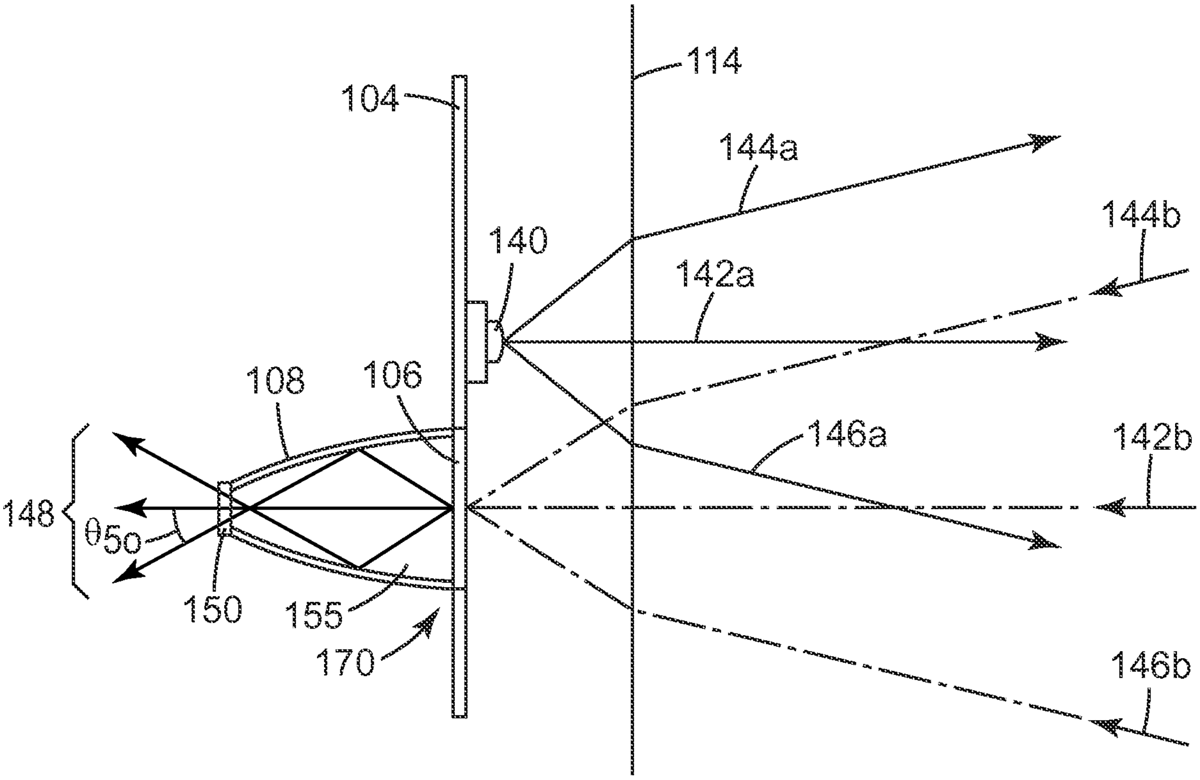
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Fig. 2E

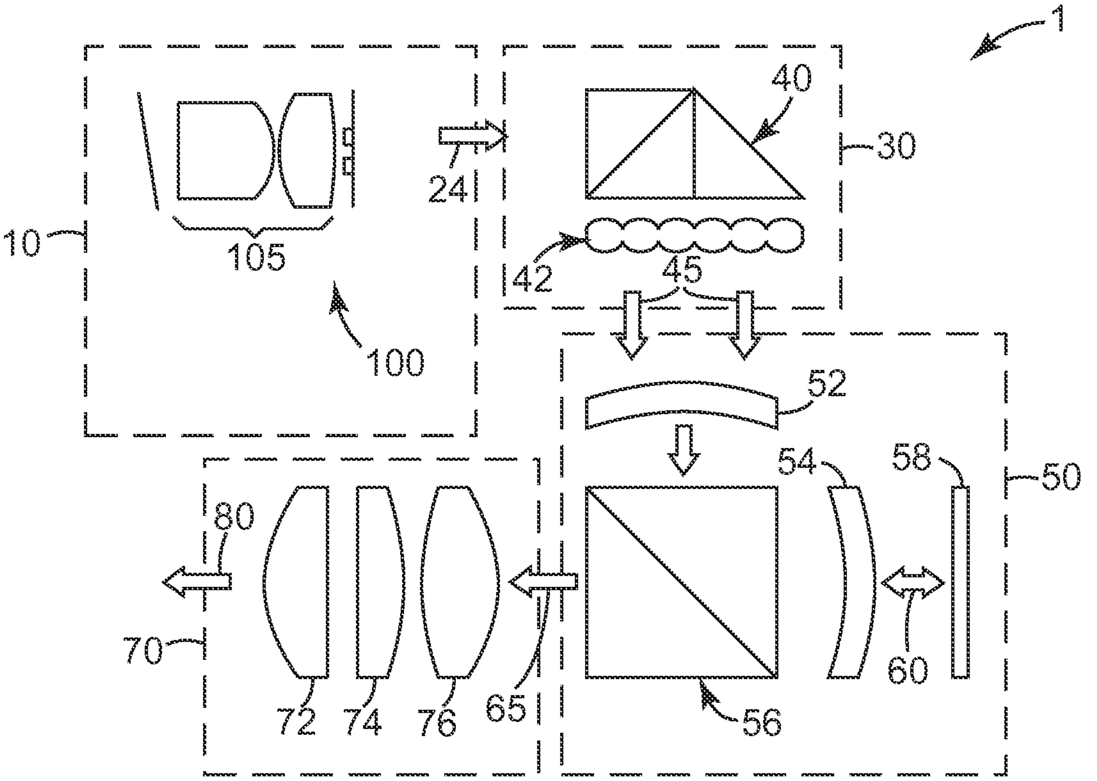
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Fig. 3