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(71) **Applicants: COELUX S.R.L.** [IT/IT]; Via Cavour 2, Polo Tecnologico ComoNExT, 22074 Lomazzo (IT). **UNIVERSITÀ DEGLI STUDI DELL'INSUBRIA** [IT/IT]; Via Ravasi 2, 21100 Varese (IT).

(72) **Inventors: DI TRAPANI, Paolo**; c/o CoeLux S.r.l., Via Cavour 2, Polo Tecnologico ComoNExT, 22074 Lomazzo (IT). **MAGATTI, Davide**; c/o CoeLux S.r.l., Via Cavour 2, Polo Tecnologico ComoNExT, 22074 Lomazzo (IT). **MOLTENI, Matteo**; c/o CoeLux S.r.l., Via Cavour 2, Polo Tecnologico ComoNExT, 22074 Lomazzo (IT). **RAGAZZI, Paolo**; c/o CoeLux S.r.l., Via Cavour 2, Polo Tecnologico ComoNExT, 22074 Lomazzo (IT).

(74) **Agent: KRAMER BARSKE SCHMIDTCHEN PATENTANWÄLTE PARTG MBB**; Landsberger Straße 300, 80687 München (DE).

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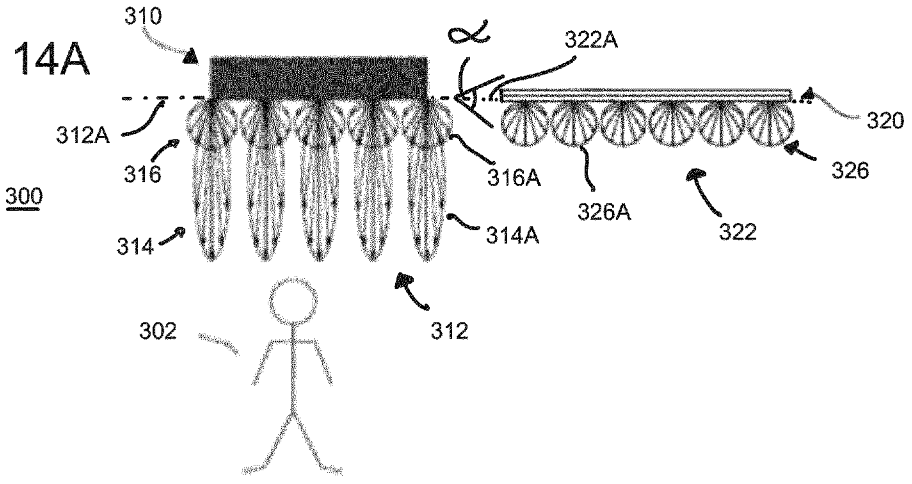
(54) **Title:** COMBINED SYSTEM FOR SUN-SKY IMITATING ILLUMINATION

FIG 14A



(57) **Abstract:** In an aspect, a combined system (300) comprises a sun-sky imitating device (310) that is configured as an artificial illumination device (20) for generating light with a luminance profile and an appearance, which feature a directed-light component (314) and a first diffused-light component (316) that are emitted from a sun-sky imitating output area (312) for imitating the natural light from the sun and the sky, respectively, and the sun-sky imitating output area (312) has a transversal dimension (D310) of at least 7 cm, wherein the transversal dimension as the longest line segment joining two points of a perimeter of the sun- sky imitating output area (312). Moreover, the combined system (300) comprises a sky imitating device (320) that is configured as an additional diffused-light emitter to emit a second diffused-light component (326) from a sky imitating output area (322) for imitating the natural light from the sky only.

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COMBINED SYSTEM FOR SUN-SKY IMITATING ILLUMINATION

Technical Field

The present disclosure relates generally to artificial illumination devices, which are based on the perception of (imitated) natural light from the sun and the sky.

Background

As disclosed, for example, in WO 2014/075721 A1, the perception of the (imitated) natural light from the sky and the sun is related both to the capacity of the illumination device to illuminate an ambient with effects very similar to the effects that would manifest in the same room if an aperture with sky and sun beyond it, *i.e.* a window, would be positioned at the same place, and also to the appearance of the illumination device itself when directly viewing at it. In some embodiments, those illumination devices can create the visual appearance of infinite depth for the sky and infinite position of the sun sources in quite compact setups.

Using Rayleigh-like diffusing layers, several applications such as WO 2009/156348 A1 WO 2009/156347 A1, and WO 2014/076656 A1, WO 2015/135560 A1 disclose lighting systems that use a light source producing visible light, and a panel containing nanoparticles used in transmission, i.e. the light source and the illuminated area are positioned on opposing sides of the panel. For details of microscopic structural properties, it is referred to, for example, the above mentioned publication WO 2009/156348 A1. During operation of those lighting systems, the panel receives the light from the light source and acts in transmission as a so-called Rayleigh diffuser (herein also generally referred to as Rayleigh panel or briefly panel), namely it diffuses incident light similarly to the earth atmosphere in clear-sky conditions. Specifically, the concepts refer to directional light with lower correlated color temperature (CCT), which corresponds to sunlight, and diffused light with larger CCT, which corresponds to the light of the blue sky. A reflective configuration is disclosed, for example, in WO 2015/172821 A1; aspects of the reflection may need to be addressed.

Moreover, WO 2017/152940 A1 discloses a sun-sky imitating lighting system with an enlarged perceived window area using a reflective element and WO 2017/084756 A1 discloses a modular sun-sky-imitating lighting system.

Generally, it is an object of the present disclosure to provide for sun/sky imitating lighting systems that may be technically less demanding, may allow smaller structural units, and may still provide for the visual comfort desired by users from lighting systems imitating natural lighting conditions. Moreover, an object of the herein disclosed concepts relates generally to extend the perception of an imitated natural sun-sky scenario, in particular near an artificial window provided by a sun-sky imitating device.

Summary of the Disclosure

Some or all of those aspects are addressed by the subject-matters of the independent claims. Further developments of the invention are given in the dependent claims.

In a first aspect, the present disclosure is directed to a combined system that comprises a sun-sky imitating device, which is configured as an artificial illumination device for generating light with a luminance profile and an appearance, which feature a directed-light component and a first diffused-light component that are emitted from a sun-sky imitating output area for imitating the natural light from the sun and the sky, respectively, and the sun-sky imitating output area has a transversal dimension of at least 7 cm, wherein the transversal dimension is the longest line segment joining two points of a perimeter of the sun-sky imitating output area. The combined system comprises further a sky imitating device that is configured as an additional diffused-light emitter to emit a second diffused-light component from a sky imitating output area for imitating the natural light from the sky only and the sky imitating output area has a transversal dimension that is the longest line segment joining two points of a perimeter of the sky imitating output area. The sun-sky imitating device and the sky imitating device are placed one with respect to the other at a distance smaller than a predefined value. The predefined value may be given by 10 times the maximum of the transversal dimension of the sun-sky imitating device and the transversal dimensionof the sky imitating device.

In another aspect, a control method for operating a combined system comprises the step that a color of a diffused light portion of the second diffused light component emitted by the sky imitating device is controlled based on a distance from the sun-sky imitating device to a point of emission of the diffused light portion.

In another aspect, a combined system comprises a directed light source that is configured as an artificial illumination device for generating light with a luminance profile and an appearance, which feature a directed-light component that is emitted from a directed-light output area for imitating the natural light from the sun and the directed-light output area has a transversal dimension of at least 7 cm, wherein the transversal dimension as the longest line segment joining two points of a perimeter of the sun-sky imitating output area. The combined system comprises further a sky imitating device that is configured as a diffused-light emitter to emit diffused light including a first diffused-light component and a second diffused-light component, wherein the first diffused-light component is emitted from the directed-light output area for adding the imitation of natural light from the sky to the imitation of the natural light of the sun, and the second diffused-light component is emitted from a sky imitating output area for imitating the natural light from the sky only.

Further embodiments of the above aspects, are disclosed in the dependent claims, which are incorporated herein by reference. For example, in some embodiments, the predefined value is given by 5 times, preferably 3 times the maximum of the transversal dimension of the sun-sky imitating device and the transversal dimension of the sky imitating device. Moreover, the transversal dimension of the sun-sky imitating device may be at least 10 cm such as at least 15 cm. In addition or alternatively, the sun-sky imitating device and the sky imitating device may be carried by a common support structure and/or share a common housing.

In some embodiments, the sun-sky imitating output area and the sky imitating output area may extend in respective light output surfaces, in particular planes, with an inclination angle equal to or smaller than 90°, or equal to or smaller than 45°, or equal to or smaller than 25° between the light output surfaces. Furthermore, the inclination angle between the light output surfaces may be smaller than 20° or 15° or the light output surfaces may form substantially parallel planes or the light output surfaces extend each other.

In some embodiments, the sun-sky imitating device comprises a collimation and/or folding optics, and a direction and a full width at half maximum of a luminance intensity distribution of the directed-light component is formed by the collimation and/or folding optics.

In some embodiments, the first diffused-light component and the second diffused-light component are chromatically similar, wherein two colors are considered similar if their color difference is equal to or smaller than 4 times, preferably equal to or smaller than 3 times, even more preferably equal to or smaller than 2 times a just noticeable difference defined in CIE76 color space, or have a chromatic difference limited by natural chromatic appearances. The first diffused-light component and the second diffused-light component may have luminance values that differ by a luminance value difference of the first diffused-light component with respect to the second-diffused light component that is less than 3 times, 2 times or even 1.5 times the larger luminance value of the first diffused-light component and the second-diffused light component.

In some embodiments, the sun-sky imitating output area is substantially surrounded by the sky imitating output area. Additionally or alternatively, the emitting side of the combined system may comprise an inner region such as a hexagonally shaped region and an outer region surrounding the inner region, and the sun-sky imitating output area may be provided in the inner region, and the sky imitating output area may be provided in the outer region.

In some embodiments, the sky imitating device is configured as an additional diffused-light source that is provided additionally to a diffused light source of the sun-sky imitating device. Additionally or alternatively, the sky imitating device is configured as a diffused light source that is partly used as a component of the sun-sky imitating device to emit the first diffused-light component from the directed-light output area associated with a directed light source, and partly used to emit the second diffused-light component from the diffused-light output area. In some embodiments, the sky imitating output area may be larger than 1.2 times the sun-sky imitating output area.

In some embodiments, the sky imitating device is configured as the additional diffused-light emitter by being configured as one of a display such as an OLED display or an LCD display, a backlight device, which comprises a plurality of light emitting devices, such as LEDs, and a diffuser downstream of the light emitting devices, and a side-lit device, which comprises a diffuser panel and a plurality of light emitting devices that emit into the diffuser panel from an edge of the diffuser panel.

In some embodiments, the sun-sky imitating device comprises a direct-light source comprising a plurality of first light emitting devices, such as LEDs, with in particular a circular aperture, configured to produce directional light as a basis for the directed-light component for imitating the natural light from the sun, and a diffused-light source configured to emit the diffused-light component for imitating the natural light from the sky. Thereby, the sun-sky imitating output area is a common output area that is defined in a light output surface of the sun-sky imitating device and emits the directed-light component and the first diffused-light component. Optionally the sun-sky imitating device further comprises collimation optics with refractive and/or reflective properties and, when the direct-light source comprises a plurality of LEDs, respective collimation optical elements of the collimation optics are associated to the LEDs of the plurality of the LEDs and are in particular more than 2 times bigger than an LED of the plurality of the LEDs. Moreover, optionally the sun-sky imitating device further comprises light absorbing material placed between the first light emitting device and the related collimation optics.

In some embodiments of the combined system, the direct-light source is configured to emit a primary light, and is associated with a first emitting surface positioned downstream the first light-emitting device, the diffused-light source is at least partially light-transparent and positioned downstream of the first light-emitting device, wherein the diffused-light source is associated with a second emitting surface and is configured to cause the first diffused-light component at the second emitting surface. The sky imitating device, which is configured as the additional diffused-light emitter, may be positioned such that the sky imitating output area is laterally shifted with respect to the sun-sky imitating device so that the primary light does not impinge on the additional diffused-light emitter, and the additional diffused-light emitter may comprise a diffused-light emitting surface, which is associated with the diffused-light output area, and is configured to emit the second diffused-light component at the diffused-light emitting surface. In addition, the direct-light source maybe configured so that, with the diffused-light source being removed if positioned upstream of the first emitting surface, the direct-light source produces from the primary light the directed-light component that exits the first emitting surface with a luminance profile which has a peak in the angular distribution around a direct-light direction. One of the first emitting surface and the second emitting surface may be positioned downstream with respect to the other and forms the sun-sky imitating output area of the sun-sky imitating device or both the first emitting surface and the second emitting surface coincide to form the sun-sky imitating output area of the sun-sky imitating device. Thereby, the sun-sky imitating device may be configured such that the direct-light source and the diffused-light source co-operate to form at the sun-sky imitating output area. The first diffused-light component, which propagates along directions spaced apart from the peak, has a correlated color temperature, and the directed-light component has a correlated color temperature that is lower than a correlated color temperature of the first diffused-light component. The second diffused-light component may have a correlated color temperature optionally corresponding to the correlated color temperature of the first diffused-light component.

Generally, the chromaticity values and/or the luminance of the first diffused-light component and the second diffused-light component may vary according to a relative distance between a point of the emission on the sky imitating output area and a reference point, such as optionally the barycenter, of the sun-sky imitating output area associated with the first diffused light component.

In some embodiments, the common output area of the sun-sky imitating device may be part of an outer emitting surface of the combined system, the outer emitting surface being the minimum area from which the light produced by the combined system emerges and propagates into the ambience, wherein the direct-light source is configured to produce the directed-light component at the outer emitting surface with a luminance profile, which has a peak in the angular distribution around a directed-light direction, wherein the directed-light component exits from at least 10% and less than 90% of the area of the outer emitting surface, wherein the combined system is configured such that the direct-light source and the diffused light source (and the at least one sky imitating device co-operate to form an outer light, which exits from the outer emitting surface.

In some embodiments, the sun-sky imitating device may structurally coupled to the sky imitating device, in particular for forming a continuity of a sky perception.

The combined system may further comprise a photovoltaic system mounted at an external surface of the combined system, which is exposed to an outdoor, and in particular wherein the photovoltaic system is positioned on the sun-sky imitating device and/or on the sky imitating device. The combined system may be integrated in a vehicle, such as in a roof of a car or in a transportation unit such as a train or plain. The combined systems may be a part of a main casing of the vehicle, and in particular the emitted light may exit the combined system to light an internal environment of the vehicle, and an external surface of the combined system is exposed to an external environment. The external surface may be in particular exposed to external light such as the sunlight, and a photovoltaic system is provided at the external surface to produce electric energy from the external light. The combined system may further comprise a battery used to store the energy collected by the photovoltaic system and to power the combined system.

In some embodiments, the sky imitating device and/or a folding mirror of the sun-sky imitating device comprise an output surface that is curved in at least one direction. The sun-sky imitating device may comprises a housing that defines a footprint of the sun-sky imitating device, and the sky imitating device is positioned to recover the usage of an area associated with the footprint.

A sky imitating device as disclosed herein may be configured to be used in a combined system as described herein, wherein the sky imitating device further comprises a light shutter layer with a light shutter, that is in particular positioned upstream of a diffuser of the sky imitating device. Such a sky imitating device ay be installed in a combined system such that, for an operation state, in which the sun-sky imitating device and the sky imitating device emit, any image forming light coming from an exterior is absorbed by the light shutter being in a closed state, and for an operation state, in which the sun-sky imitating device and sky imitating device are turned off, the light shutter is in an open state and transmits light from the exterior.

Such a sky imitating device, installed in a combined systemnext to a transparent window, may have a light shutter that comprises a layer of a light absorbing material that is configured such that, in an open state of the light shutter, the light absorbing material layer is mechanically moved away from the transparent window, and in a closed state of the light shutter, the light absorbing material layer is positioned to cover the transparent window.

In some embodiments of sky imitating device, the light shutter layer is made of a tunable smart material, in which light transmitting properties are electronically tunable, such as electrochromic, electro-wettable or Polymer Dispersed Liquid Crystals (PDLC) materials.

Brief Description of the Drawings

Other features and aspects of this disclosure will be apparent from the following description and the accompanying drawings. The accompanying drawings, which are incorporated herein and constitute a part of the specification, illustrate exemplary embodiments of the disclosure and, together with the description, serve to explain the principles of the disclosure. In the drawings:

Fig. 1	schematically shows an artificial illumination device illustrating a luminance profile of directed light component;
Fig. 2	shows a sectional view of an array of LEDs appropriately configured to result in an appropriate direct-light source in accordance with an embodiment;
Fig. 3	shows a top-view of the array of Fig. 2;
Fig. 4	shows a schematic partial perspective view of a direct-light source in accordance with an embodiment, comprising a pair of a first light-emitting device and a collimating lens;
Fig. 5	shows 3-dimensionally an array of pairs in accordance with Fig. 4 so as to result in a direct-light source in accordance with a further embodiment;
Fig. 6	shows a schematic of an edge-illuminated lightguide emitter panel in accordance with an embodiment;
Fig. 7	shows an alternative embodiment for an edge-illuminated lightguide emitter panel;
Fig. 8	schematically shows an artificial illumination device including a low-angle white-light diffuser positioned upstream the diffused-light generator;
Fig. 9	schematically shows a further embodiment of an artificial illumination device including a low-angle white-light diffuser which is, however, positioned downstream the diffused-light generator;
Fig. 10A-C	schematically shows an artificial illumination device including a combination of a direct-light source and a diffused-light generator with additionally illustrating the CCT offset between direct, transmitted and diffused light;
Fig. 11	schematically shows a diffuser panel for implementing the diffused-light generator;
Fig. 12A/B	schematically show combinations of a diffuser panel and a diffused-light source for implementing the diffused-light generator;
Fig. 13	schematically shows a diffused-light source for implementing a diffused-light generator;
Fig. 14A-C	schematically show combined systems for sun-sky imitating illumination;
Fig. 15	schematically shows an exemplary embodiment of combined system;
Fig. 16A/B	schematically show further exemplary embodiments of combined systems;
Fig. 17A/B	schematically show further exemplary embodiments of combined systems;

Fig. 18 A/B	schematically show exemplary embodiments of combined systems for installation in vehicles;
Fig. 19	schematically shows another exemplary embodiment of a combined system; and
Fig. 20	schematically shows controlling luminance and chromaticity in combined system.

Detailed Description

The following is a detailed description of exemplary embodiments of the present disclosure. The exemplary embodiments described therein and illustrated in the drawings are intended to teach the principles of the present disclosure, enabling those of ordinary skill in the art to implement and use the present disclosure in many different environments and for many different applications. Therefore, the exemplary embodiments are not intended to be, and should not be considered as, a limiting description of the scope of patent protection. Rather, the scope of patent protection shall be defined by the appended claims.

The disclosure is based in part on the realization that known sun and sky imitating illumination systems providing sunlight and skylight from a common output area may be improved based on systems comprising sun-sky imitating devices, sun imitating devices, and sky imitating devices. It was realized, for example, that the effects achieved with a sun-sky imitating device can be extended to additional sky imitating devices by additionally providing such sky imitating devices in the proximity of the sun-sky imitating device and that those combined systems for illumination allow further implementations of configuration with specific effects. Thereby, a sun-sky imitating device offering infinite depth perception may allow also a sky (only) imitating device as (close by) to offer as well infinite depth perception. Moreover, it was realized that optical effects may be achieved with a plurality of sun imitating devices set within a bezel (bezel cluster) forming a system for illumination. Specific configurations of the plurality of sun imitating devices and/or the bezel may allow further implementations with specific effects. Thus, the concepts disclosed herein may broaden the field of technical implementations of sun and sky imitating illumination systems.

In the following, at first general aspects will be described for those new concepts. Then, exemplary embodiments of sun-sky imitating light devices, sun imitating devices, and sky imitating devices will be described in connection with Figs. 1 to 13 thereby for convenience starting from implementations of sun-sky imitating devices. Thereafter, specific embodiments illustrating the claimed-subject matter are described, in particular in connection with Figs. 13 to 20.

As introduced in WO 2014/075721 A1 mentioned above, the perception of (imitated) natural illumination from sky and sun relies on the one side on the light emitted by the illumination device and on the perception of infinite depth of the sky and sun images when directly viewing at the illumination device itself. The emitted light should feature a direct-light component highly collimated with low CCT, mimicking the light from the sun, and a higher CCT diffused-light component, mimicking the illumination effect of the sky.

The capability of an observer to evaluate the distance of objects, and therefore the depth of the views that constitute a three-dimensional scenery, is based on multiple physiological and psychological mechanisms connected to focusing, binocular disparity and convergence, motion parallax, luminance, size, contrast, aerial perspective, etc. Some mechanisms may gain significance compared to the others according to both the observing conditions (*e.g*, whether the observer is moving or still, watching with one or two eyes, etc.) as well as the characteristics of the scenery, these latter depending, for example, on whether objects with known size, distance or luminance are present, serving as a reference to evaluate how distant the observed element of the scenery is. Notably, these mechanisms hold both in the case of real images and of virtual images. The teaching disclosed in WO 2014/075721 A1 applies in particular if both eyes see respective images and the above indicated art proposed to enhance the infinite depth perception by binocular vergence.

The concepts disclosed herein may allow the creation of an infinite depth perception even without a large sun-sky imitating output area; e. g., a size of a sun-sky imitating output area (or sun imitating output area) may essentially have a size that does not enable binocular vergence by itself.

Some of the concepts extend the perception of a natural scenario near an artificial window (i. e., a sun-sky imitating device), even without a further sun-sky imitating device being directly present next to a sun-sky imitating output are; instead there is an area that may not emit light or may lack a component (e. g., there is only imitation of skylight or sunlight). Respective combined systems may combine at least one sun-sky imitating device and at least one sky imitating devices.

Some of the concepts are based on a specific combination of sun-sky devices (or sun devices), which have a peak in the angular distribution of the luminance profile. However, respective sun-sky (or only sun) imitating output areas are well separated. E. g., a distance between the two nearest point of such output areas may be larger than 3 cm.

In some systems, a sun-sky imitating device may enhance (drive) the perception of an area as a natural window, while using a sky imitating device (e.g. configured as an additional diffused-light emitters) extends the scenario naturally, thereby giving a visual perception continuum.

The concepts may require less technology and/or smaller components, and nonetheless obtain a natural mimicking effect; however, at lower cost per area, for example. Moreover, smart specific placement of the sun-sky imitating devices, sun imitating devices, and sky imitating devices, in particular in specific embodiments switchable in transmission, may preserve a panorama view intended, e. g., for a car roof, when sun-sky imitating devices are switched off. Similarly, an additional natural window imitation (or part of window) may be achieved, where only sky is visible.

The inventors realized that, once the distance between two nearest points belonging to two different sun-sky imitating devices, for example, becomes larger than the pupillary distance (e. g., larger than 3 cm), binocular cues, such as binocular disparity or convergence may not provide enough data to give the correct perception under all the possible observer's positions. It should be noted that the binocular disparity might be impaired when the area which emits the directed-light component, is less than 80 % of the surface of the device, or less than 50 %, or less than 30 %.

Surprisingly, it has been found that a motion parallax cue related to a light source at a substantially infinite distance – thus the parallelism between sun rays – and the presence of a frame also may provide sufficient cues to create the depth perception; in that case, even without any binocular cues able to provide depth information. Moreover, as natural, the presence of the frame might be occasionally annoying if the percentage of occupied area is high. Nevertheless, the perceived naturalness of the light coming from such system may not be affected.

At the same time, it is clear that in this way it is possible to obtain a certain area to be illuminated, where the effect is targeted, while having a minor quantity of active area. In fact, this means that it is possible to spread over a surface (e. g., of a ceiling surface) a plurality of sun-sky imitating devices, effectively enlarging the total occupied area (Occupied by structural elements of the various illumination devices), while essentially not affecting the perception of that area. An essentially unaffected perception may be the case, even if one introduces certain zones, which do not produce any directed light. In this sense, the active areas of, e.g., the sun-sky imitating devices, may create an enhancement of the effect that operates also on different areas (the non-active areas).

In some embodiments, the areas (of, e. g., the ceiling), which do not produce directed light, produce (additional) diffused light, whereby the diffused light component produced by a sun-sky imitating device and the additional diffused light component may have an adequate similarity so that the diffused light contributions coming from different positions are perceived as belonging to the same natural scenario. E. g., for the diffused light mimicking the sky, the two colors should be similar or at least naturally different (where naturally different means that it is a realistic difference, similar to what happens in nature). In some embodiments, two colors may be considered similar if their color difference is equal to or smaller han 4 times, preferably 3 times, even more preferably 2 times the "just noticeable difference" in CIE76 color space (CIELAB). In this context it is referred also, e.g., to Wikipedia on "Color difference", specifically the section on CIE76 referring to two colors in CIELAB color space, (L_1^*, a_1^*, b_1^*) and (L_2^*, a_2^*, b_2^*), whereby the CIELAB color space expresses color as three numerical values, L^* for the lightness, and a^* and b^* for the green–red and blue–yellow color components.

Then, $\Delta E_{ab}^* = [(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2]^{1/2}$ defines the CIE76 color difference, and the value $\Delta E_{ab}^* \approx 2.3$ corresponds to the "just noticeable difference".

It was realized that such an entire system (combining various types of devices in a combined system) may be perceived as a combination of apertures through which the sun can be seen; the (imitated) sunlight being perceived as passing at least somewhere through apertures, while through other apertures, some portion of the (imitated) sky is visible. Thus, in some embodiments, a combined system may provide "user areas" where the sun is visible and "scenario areas" in which only sky imitation is needed.

Generally, a system in line with the concepts disclosed herein may comprise sun-sky imitating devices and/or and sun imitating devices as well as devices providing areas emitting only diffused light or non-emitting at all.

Those non-emitting areas together may be associated with a bezel or bezel cluster that encompasses a plurality of sun-sky imitating devices and/or and sun imitating devices. Thus, some systems may be constituted by a bezel and one or more sun-sky imitating devices, whereby the sun-sky imitating devices fill the apertures of the bezel/bezel cluster. In some embodiments, the bezel may be switchable from being opaque to transparent.

Systems in line with the concepts disclosed herein may need less or less complex technology and, thus, may be cost saving, assuming the bezel implementations are kept inexpensive.

Solutions in line with the concepts disclosed herein may be adequate also to create a combination of sun-sky imitating device and a sky-only imitating device for architectural targets. Such a sky-only imitating device might cover a wall or ceiling and create the natural continuation (combination) of a window where the sun enters. It should be noted that it is natural that some windows may not be lit by the sun, for example, because the same may be hidden by other building or natural structures or because the same may be facing different directions with respect to the sun direction.

It should be noted further that the combined systems described herein may comprise sun-sky devices and additional diffused light emitters, and/or light shutters, and/or inactive areas.

For example, when considering a certain extension of the total area that produces light, the concepts presented herein may create a natural scenario as a sun-sky imitating device, but may require less energy (e. g., than an array of sun-sky imitating devices), as directed light is not created from every point of the emitting surface. Moreover, the same area size may be covered using a minor number of elements, reducing the cost.

Furthermore, when considering an area, e. g., of a ceiling that is not possible to fully cover with sun-sky imitating devices (for example, because there is a need to maintain transparency in certain zones), implementations comprising at least one transparent portion (in particular transparent in the visible color spectrum) in addition to one or more sun-sky imitating portions may extend the total area perceived as natural. Similarly, sun-sky imitating devices may have a footprint that is larger than the emitting area (here the sun-sky imitating output area). In consequence, a certain inactive areas may be present when installing the system. Then, an additional diffused-light emitter may be used to recover such inactive area for illumination.

The following devices, components, and features may exemplarily refer to features of embodiments described below in connection with the drawings or as known from the above mentioned publications.

- A sky imitating device may be configured as an additional diffused-light emitter. For example, the diffused-light source 260 or the diffused light generator 10 mentioned before may act as a sky imitating device in so that it emits only diffused-light component. A diffused-light emitter can in general be partially transparent, e.g. when used in some section, to transmit a directed-light component.
- A sun imitating device may be configured as a direct-light source 12 and produces a directed-light component.
- A sun-sky imitating device may be configured as an artificial illumination device for generating light imitating the natural sunlight and the natural skylight. Thus, light emitted may

have a luminance profile and an appearance similar to that of the light from the sun and the sky.
- A directed-light component mimicking the sunlight may be considered a “warm” (low CCT) light (such as transmitted light portion 238).
- A diffused-light component mimicking the skylight may be considered a “cold” (high CCT) light (diffused light 242).
- Primary sources, in which the initial generation of primary light takes place, are referred to as first light-emitting device, e. g., LEDs such as light-emitting devices 14, 46, 60, 114, 138, or 150.
- Primary light can be shaped with collimation optics. A light collimation optics may comprise collimation optical elements such as dome lens, Fresnel lens, or microlens 48, 64.
- The angular distribution of luminance of sun-imitating devices is defined point by point and is herein characterized by a peak (herein also as “narrow” indicated), wherein a peak is a portion of the angular distribution of luminance having a maximum and a full width half maximum (FWHM), which is significantly smaller than 2pi sr, e.g. smaller than 0.4 sr, preferably smaller than 0.3 sr, more preferably smaller than 0.2 sr. In each portion of a sun-sky imitating output area or a sun imitating output area, the (narrow) peak is given. This means also that the (narrow) peak contains the majority of the flux exiting from that portion of the emitting surface, e. g., more than 60 % of the luminous flux is contained in the peak, preferably more than 80 %, more preferably more than 95 % of the luminous flux.
- The luminous intensity distribution (LID) is the far-field projection of the luminance. The LID considers accordingly the angular components of light emitted from a source region. Therefore, the angular distribution of the LID is defined as the integration of the luminance over an area of the source region.

Fig. 1 illustrates an embodiment of a sun-sky imitating device, which is capable of illuminating an ambience as the sun and the sky do through a window. The sun-sky imitating device can be configured for a visual appearance that guarantees the experience of virtually infinite depth as the sky and the sun do in nature when they are observed through a window. In other terms, the embodiment illustrates an artificial illumination device 20 for generating natural light as the sun and the sky, *i.e.* having a luminance profile and an appearance similar to that of the light from the sun and the sky.

A sun-sky imitating device that is configured as an artificial illumination device 20 of Fig. 1 comprises a direct-light source 12 with a first emitting surface 28. The direct-light source 12 comprises, for example, a first light-emitting device configured to emit primary light and positioned upstream relative to the first emitting surface 28. The direct-light source 12 is configured to produce from the primary light a directed light 236 which exits the first emitting surface 28 with a luminance profile $L_{direct}(x, y, \vartheta, \varphi)$. The luminance profile $L_{direct}(x, y, \vartheta, \varphi)$ is uniform (e.g. with respect to the spatial dependence) across the first emitting surface 28 and has a (narrow) peak 30 (i. e. with respect to the angular dependence) along a direct light direction 32. x and y are the transverse coordinates along axes x and y spanning the first emitting surface 28, ϑ is the polar angle measured relative to the direct-light direction 32, and φ is the azimuthal angle. Although the term “narrow” is rendered more clear below, in general it might be interpreted as saying that $L_{direct}(x, y, \vartheta, \varphi)$ has a peak subtended by a solid angle which is significantly smaller than $2\pi\cdot$sr, e. g. smaller than 0.4 sr, preferably smaller than 0.3 sr, more preferably smaller than 0.2 sr.

Moreover, the artificial illumination device of Fig. 1 also comprises a diffused-light generator 10. The diffused-light generator 10 comprises a second emitting surface 34 and an input surface 33 facing opposite to the second emitting surface. The diffused-light generator 10 is configured to be, at least partially, transparent to the light impinging onto the input surface 33. Moreover, the diffused-light generator 10 is configured to emit a diffused light 35 from the second emitting surface 34, wherein said diffused light 35 is the component of outer light which exist the second emitting surface 34 being scattered in virtually all forward directions and being uniform or at least weakly dependent on the spatial coordinates x,y. For example, the diffused-light generator 10 is configured to emit a diffused light over a solid angle which is at least 4 times larger, preferably 9 times larger, more preferably 16 times larger than the solid angle subtending the (narrow) peak 30.

In addition, the device of Fig. 1 can be configured so that the directed light 236 produced by the direct-light source 12 has a CCT (correlated color temperature), which is lower than a CCT of the diffused light 35 (*e.g.* at least 1.2 times lower, preferably 1.3 times lower, more preferably 1.4 times lower). Owing to the fact that the diffused-light generator 10 is at least partially light-transparent, at least a portion of the directed light 236 propagates downstream the second emitting surface 34. As a consequence, the outer light comprises a directed-light component which propagates along directions contained within the peak 30 (for example along at least 90% of the directions subtending the peak 30, *i.e.* 90% of the directions with polar angle ϑ smaller than the HWHM polar angle of the peak) and a diffused-light component which propagates along directions spaced apart from the narrow peak 30, *e.g.* directions spanning at least 30%, preferably 50%, most preferably 90% of the angular region outside the cone with axis directed along direction 32 and half-aperture 3 times larger than the HWHM polar angle of the narrow peak, wherein the first light component has a CCT which is lower than a CCT of the second light component (*e.g.* at least 1.2 times lower, preferably 1.3 times lower, more preferably 1.4 times lower).

It will be understood that the mutual positions of the first emitting surface 28 and the second emitting surface 34 within a sun-sky imitating device can be inverted with respect to the case of Fig. 1, or the first emitting surface 28 can coincide with the second emitting surface 34.

As a further particular case of an embodiment, a sun-sky imitating device is possible wherein the process of transforming the primary light into the directed light (*e.g.* the collimation process) is performed by a few optical elements positioned upstream of the first emitting surface 28, and wherein the diffused-light generator 10, positioned upstream of the first emitting surface 28, is neither directly lit by the primary nor by the direct light, but it is lit by an intermediate light evolving from the primary light and resulting in the direct-light at the first emitting surface 28.

A further, more general, embodiment of a sun-sky imitating device comprises:

a direct-light source 12; and
a diffused-light generator 10,

wherein the direct-light source 12 comprises a first light-emitting device 14 configured to emit a primary light, and a first emitting surface 28 positioned downstream the first light-emitting device,

wherein the diffused-light generator 10 is at least partially light-transparent and is positioned downstream the first light-emitting device and comprises a second emitting surface 34 and is configured to cause diffused light 35 at the second emitting surface 34,

wherein the direct-light source 12 is configured so that, with the diffused-light generator 10 being removed if positioned upstream the first emitting surface 28, the direct-light source 12 produces from the primary light directed light 236 that exits the first emitting surface 28 with a luminance profile which is uniform across the first emitting surface 28 and has a (narrow) peak 30 in the angular distribution around a direct-light direction 32,

wherein one of the first emitting surface 28 and the second emitting surface 34 is positioned downstream with respect to the other and forms an outer emitting surface of the sun-sky imitating device or both the first emitting surface 28 and the second emitting surface 34 coincide to form the outer emitting surface of the sun-sky imitating device,

wherein the sun-sky imitating device is configured such that the direct-light source 12 and the diffused-light generator 10 co-operate to form outer light at the outer emitting surface which comprises a first (directed) light component which propagates along directions contained within the (narrow) peak 30 (for example along at least 90% of the directions subtending the (narrow) peak 30) and a second light component which propagates along a directions spaced apart from the narrow peak 30 (for example along directions spanning at least 30%, preferably 50%, most preferably 90% of the angular region outside the cone with axis directed along direction 32 and half-aperture 3 times larger than the HWHM polar angle of the narrow peak),

wherein the first light component has a CCT which is lower than a CCT of the second light component, for example 1.2 times lower, preferably 1.3 times lower, most preferably 1.4 times lower.

The embodiments of a sun-sky imitating device include a direct-light source featured by a luminance profile $L_{direct}(x, y, \vartheta, \varphi)$ which is at the same time uniform with respect to the spatial coordinates, and (narrowly) peaked with respect to the angular coordinate. As the diffused-light generator is at least partially light-transparent, the actual features of $L_{direct}(x, y, \vartheta, \varphi)$ are essential with respect to the visual perception cues.

The presence of a uniform luminance profile along spatial coordinates with a sharp angular peak can generate a virtual image supported by binocular convergence at infinity. It is noted that the narrow peak in the $L_{direct}(x, y, \vartheta, \varphi)$ angular profile, as long as it is perceived by the two eyes from the same direction (which follows from L_{direct} spatial uniformity and the fact that it is peaked along direct light direction 32) forces the two eyes to be aligned along parallel directions, supporting infinite depth perception of a bright spot representing the sun.

The spatial uniformity of $L_{direct}(x, y, \vartheta, \varphi)$ ensures also an infinite depth perception for the visual cue of motion parallax, since a moving observer experiences the virtual image due to any angular structure of $L_{direct}(x, y, \vartheta, \varphi)$, *e.g* the narrow peak 30 which represents the sun, as moving together with him/her as very far away objects appear to move in reality.

The narrow angular peak 30 along the direct-light direction 32 ensures parallel shadows with a sharp penumbra. The diffused-light generator 10 ensures on one side that the embodiment represented in Fig. 1 illuminates an ambience as the natural sky and sun, by providing a higher CCT diffused light component which tinges shadows in a bluish color as it happens for natural light entering an actual window. On the other side, the diffused-light generator 10 affects also the visual appearance of the device itself when directly looking at it. In fact, the diffused-light generator 10 creates a diffuse luminous bluish background around the low CCT bright spot determined by the luminance of the direct-light source. This luminous background, instead of spoiling the infinite depth perception as it would happen for a white or a gray luminous background, further supports the infinite depth perception because of the synergistic action between the aerial perspective visual cue and the other visual cues, already described, supported by the direct-light source alone.

With respect to said synergistic action, a key role is played by the three concurrent effects of the peak in the L_{direct} angular profile, of the spatial uniformity and smooth angular dependence of the diffused-light emitted from the second emitting surface 34 and of the high value of the diffused-light CCT (with respect to the direct light CCT).

As described in WO 2014/075721 A1, the sun-sky imitating device may be constructed as “compact” artificial illumination device. Thereby, the direct-light source 12 may be accommodated within a cuboid, the area of the ground face of which is equal to or greater than the area of a light-emitting surface and a height h1 of which is smaller than a maximum width of the first emitting surface 28. The ground face may comprise the first emitting surface 28 or may be placed parallel thereto with the first emitting surface 28 completely residing within the cuboid. The area of the ground face may be smaller than 1.1 times the area of the first emitting surface 28. The diffused-light generator 10 may not accommodate much space. For example, the diffused-light generator 10 may be arranged within a cuboid having its ground face in the same plane as the first emitting surface 28 and extending into the downstream direction 36 by a height h2. The area of ground face may be equal to or smaller than ground face and the same applies to height h2 which may be smaller than or equal to height h1. A top face opposite to the ground face may comprise the second emitting surface 34 or the latter may be contained within the cuboid of the diffused-light generator 10. Preferably, the area of the second emitting surface 34 is approximately equal to the area of the first emitting surface 28 such as, for example, +/- 10% of the area of the first emitting surface 28. The height 10b may be smaller than 10% of the aforementioned maximum width of first emitting surface 28 or smaller than 10 cm irrespective of the maximum of first emitting surface 28. The downstream direction 36 may, for example, be defined to point into the direction 32 into which the direct light generated by direct-light source 12 is emitted from the first emitting surface 28. As said, this direction 32 may be parallel to the normal of first emitting surface 28. Alternatively, the cuboid of generator 10 may be completely contained within the direct-light source’s cuboid.

As a consequence of the direct-light source ability to produce the direct light such that same exits the first emitting surface 28 with a luminance profile L_{direct} which is uniform across the first emitting surface 28 and has the peak 30 around the direct-light direction 32, it follows that: 1) the direct-light direction 32 is substantially constant all over the first emitting surface 28, 2) the divergence is small (related to the peak), and 3) the divergence is substantially constant over all the first emitting surface 28. An observer who looks at the direct-light source and its first emitting surface 28, respectively, sees a bright spot under a narrow visual cone angle, the spot being perceived at infinite distance with respect to binocular-convergence, accommodation and motion parallax depth cues. In other words, the observer sees, when looking towards the first emitting surface 28, a bright spot which, when the observer moves relative to the light-emitting surface, moves relative to the first emitting surface 28 as if the bright spot stemmed from an object positioned at infinity.

In particular, the direct-light source 12 emits light with uniform intensity across the first emitting surface 28 at single, given direction 32 with respect to the emitting surface's normal z, with very low, preferably circular symmetric, divergence cone and low background outside such divergence cone, where both the divergence and the background are also uniform across the panel. In this regard, $L_{direct}(x, y, \vartheta, \varphi)$ shall denote the luminance of the direct light as generated by the direct-light source at a dark environment, *i.e.* without any light originating or reflected from outside the direct-light source, where x, y, ϑ and φ are as defined before. It is submitted that in expressing the luminance in function of the spatial and angular coordinates one should account for the actual angular resolution of the detector and its distance from the source, which in turn determines the detectable spatial resolution. In the context of the present invention, it is assumed an angular resolution of 0.07°, which approximates the typical naked eye angular resolution, and a spatial resolution of 1mm, which corresponds to an observation distance of about 1m. Therefore all the constraints concerning the luminance profiles described in the context of the present invention should be intended as referred to the above mentioned resolutions, in the sense that variations that eventually occur at higher angular or spatial frequencies (*i.e.* which could be detected with higher angular resolution and/or at closer distance) are not relevant for the purpose of the present invention. The constraints may be such that:

> far from direction 32, *i.e.* for polar angles $\vartheta > 3\vartheta_{HWHM}$, where ϑ_{HWHM} is the HWHM (half width half maximum) of a mean polar-angle distribution being an average over the luminance profile L_{direct} over all positions (x,y) in the light-emitting surface and all azimuthal directions φ, the luminance profile L_{direct} drops below 10%, preferably below 1%, most preferably below 0.1% of an absolute maximum of L_{direct} over all positions and angles, and
>
> close to direction 32, *i.e.* for polar angle $\vartheta \leq \vartheta_{HWHM}$, the luminance profile L_{direct} is weakly dependent from the azimuthal coordinate φ; *e.g.* for each position (x,y), the ϑ,φ region outside which L_{direct} drops below 10% of the maximum is substantially a cone with circular base, which allows the observer to perceive a round spot when looking at the source into direction 32; quantitatively, the difference between max and min polar angles of said region normalized to the half sum of the same quantities may be below 0.5, preferably below 0.2, most preferably below 0.1 for any position in the sample;
>
> wherein $\vartheta_{HWHM} \leq 2.5°$, preferably $\vartheta_{HWHM} \leq 1.5°$, more preferably $\vartheta_{HWHM} \leq 0.5°$.

In formulas, this means:

$$L_{direct}(x, y, \vartheta, \varphi) \leq k \cdot L_{\max} \qquad \text{for } (x, y) \in A,\ \varphi \in [0; 2\pi[\text{ and } \vartheta > 3\vartheta_{HWHM}$$

and

$$2\frac{\vartheta_{\max}(x, y) - \vartheta_{\min}(x, y)}{\vartheta_{\max}(x, y) + \vartheta_{\min}(x, y)} \leq h \qquad \text{for } \varphi \in [0; 2\pi[,\ (x, y) \in A \text{ and } \vartheta \leq \vartheta_{HWHM}$$

wherein

A denotes the area of the first emitting surface 28,

$\vartheta_{HWHM} \leq 2.5°$, preferably $\vartheta_{HWHM} \leq 1.5°$, more preferably $\vartheta_{HWHM} \leq 0.5°$,
k=0.1, preferably k=0.01, most preferably k=0.001,
h=0.5, preferably h=0.2, most preferably h=0.1

and wherein the following definitions hold true:

$$L_{\max} \equiv \max_{x,y,\varphi,\vartheta}\left(L_{direct}(x,y,\vartheta,\varphi)\right)$$

$$L_{mean\ \ polar\ \ angle\ \ distr}(\vartheta) \equiv \frac{1}{2\pi}\frac{1}{A}\int_{\varphi\in[0;2\pi[}\int_{(x,y)\in A} L_{direct}(x,y,\vartheta,\varphi)\,d\varphi\,dx\,dy$$

$$\vartheta_{HWHM} \equiv HWHM\left(L_{mean\ \ polar\ \ angle\ \ distr}(\vartheta)\right)$$

$$\vartheta_{\min}(x,y) \equiv \min\left\{\vartheta \middle| \forall\,\vartheta' > \vartheta, \exists\,\varphi,\ \ L_{direct}(x,y,\vartheta',\varphi) \leq 0.1\cdot L_{\max}\right\}$$

$$\vartheta_{\max}(x,y) \equiv \max\left\{\vartheta \middle| \forall\,\vartheta' > \vartheta, \exists\,\varphi,\ \ L_{direct}(x,y,\vartheta',\varphi) \leq 0.1\cdot L_{\max}\right\}$$

Putting more focus on the uniformity of the residual direct-light background far from direction 32, the request on L_{direct} is to show minimal spatial amplitude fluctuations for polar angle ϑ greater than $3\vartheta_{HWHM}$; *e.g.* the ratio between a standard deviation of said luminance spatial fluctuations and the luminance average value may not exceed the value of 0.3, preferably not exceed the value of 0.1, within any 10 mm diameter spatial circular areas and for at least 90% of the light-emitting surface, and may not exceed the value of 0.4, preferably not exceed the value of 0.3, more preferably not exceed the value of 0.2, within the entire at least 90% of the light-emitting surface, for any fixed azimuthal angle φ and for any fixed polar angle ϑ greater than $3\vartheta_{HWHM}$;

As far as direct-light uniformity close to direction 32 is concerned, the request on L_{direct} is of not exhibiting spatial fluctuations in a (local) polar angle leading to (local) maximum luminance with standard deviation larger than 20% of ϑ_{HWHM} within spatial areas of 5 cm diameter, preferably 10 cm diameter, more preferably 20 cm diameter, and does not exhibit spatial fluctuations in the (local) polar angle leading to (local) maximum luminance with standard deviation larger than ϑ_{HWHM} within the entire at least 90% of the entire light-emitting surface, wherein $\vartheta_{HWHM} \leq 2.5°$, preferably $\vartheta_{HWHM} \leq 1.5°$, most preferably $\vartheta_{HWHM} \leq 0.5°$.

Described in formulas, the just mentioned constraints can be formulated as

$$\sigma_{x,y}\left(L_{direct}(x,y)\big|_{\vartheta,\varphi}\right) \leq j\cdot\mu_{x,y}\left(L_{direct}(x,y)\big|_{\vartheta,\varphi}\right),$$

for $(x,y)\in A_{10\,mm}(X,Y)$, $\forall\,\varphi\in[0;2\pi[$ and $\forall\,\vartheta > 3\vartheta_{HWHM}$,
with j=0.3, preferably j=0.1

$$\sigma_{x,y}\left(L_{direct}(x,y)\big|_{\vartheta,\varphi}\right) \leq g\cdot\mu_{x,y}\left(L_{direct}(x,y)\big|_{\vartheta,\varphi}\right),$$

for $(x,y)\in A_{90\%}$, $\forall\,\varphi\in[0;2\pi[$ and $\forall\,\vartheta > 3\vartheta_{HWHM}$,
with g=0.4, preferably g=0.3, more preferably g=0.2.

$$\sigma_{x,y}\left(\arg\max_{\vartheta}\ L_{direct}(\vartheta,\varphi)\big|_{x,y,}\right) \leq 0.2\cdot\vartheta_{HWHM} \qquad \text{for } (x,y)\in A_{diam}(X,Y),$$

$$\sigma_{x,y}\left(\arg \max_{\vartheta} L_{direct}(\vartheta,\varphi)\Big|_{x,y,} \right) \le \vartheta_{HWHM} \qquad \text{for } (x,y) \in A_{90\%}$$

wherein all $(X,Y) \in A_{90\%}$, $\vartheta_{HWHM} \le 2.5°$, preferably $\vartheta_{HWHM} \le 1.5°$, most preferably $\vartheta_{HWHM} \le 0.5°$, and with $A_{90\%}$ denoting a portion taking up 90% of the whole area of the first emitting surface 28 which portion may be simply connected or not, A_{10mm} denoting any circular area of 10 mm diameter at (X;Y) within A, A_{diam} denoting a circular area at (X;Y) within A of 5 cm diameter, preferably 10 cm diameter, more preferably 20 cm diameter, $\sigma_{x,y}$ denoting the standard deviation of the argument with respect to the spatial coordinates, $\mu_{x,y}$ denoting the mean value of the argument with respect to spatial coordinates, and wherein the following definitions hold true:

$L_{local\ \max}\Big|_{x,y} \equiv \max_{\vartheta,\varphi} L_{direct}(\vartheta,\varphi)\Big|_{x,y}$ (*i.e.* a maximum luminance at given position) and

$\arg \max_{\vartheta} L_{direct}(\vartheta,\varphi)\Big|_{x,y} \equiv \left\{ \vartheta \,\Big|\, \exists\, \varphi \,\Big|\, L_{direct}(\vartheta,\varphi)\Big|_{x,y} = L_{local\ \max}\Big|_{x,y} \right\}$ (*i.e.* a polar angle at which said maximum luminance at given position occurs)

and wherein

$$L_{direct}(x,y)\Big|_{\vartheta,\varphi} \equiv L_{direct}(x,y,\vartheta',\varphi') \qquad \text{for } \vartheta' = \vartheta, \varphi' = \varphi,$$

$$L_{direct}(\vartheta,\varphi)\Big|_{x,y} = L_{direct}(x',y',\vartheta,\varphi) \text{ for } x' = x, y' = y$$

Summarizing, by the above constraints it can be assured that for polar angles sufficiently spaced apart from the direct-light direction 32, L_{direct} is fairly weak and uniform, while for polar angles close to direct-light direction 32, L_{direct} is weakly dependent on azimuthal coordinate, and is peaked at the same direction, *i.e.* $\vartheta = 0$, for any $(x, y) \in A$, at least substantially, so that the appearance of a round spot is assured. As denoted above, by these constraints it is assured that the observer will see only a bright and round spot, with full-width angular size equal to, or similar to, $2 \cdot \vartheta_{HWHM}$, surrounded by a weak and uniform background.

In a certain embodiment, the direct-light source is configured to ensure dark and uniform background also when it is operated inside a fairly luminous environment, *i.e.* it is configured so that ambient light is not reflected or back scattered in an amount which may spoil the appearance of the first emitting surface 28 in terms of background luminance level and uniformity. In fact, in use, the first emitting surface 28 not only emits but also may receive light from, for example, the diffused-light generator 10 (if positioned downstream of it) and/or from the ambience. For example, in the ideal case of the artificial illumination device 20 illuminating a perfectly white room, the entire luminous flux generated by the direct-light source would return to the direct-light source itself.

The request of above translates into a request for the first emitting surface 28 to have a dark and uniform appearance under diffuse external illumination when the direct-light source 12 is off. Specifically, in the present embodiment the direct-light source 12 is configured so that the first emitting surface 28 has a total reflectance (average) factor $\eta_r \le 0.4$, preferably $\eta_r \le 0.2$, more preferably $\eta_r \le 0.1$, even more preferably $\eta_r \le 0.04$, wherein the total reflectance factor η_r is defined as the ratio of the luminous flux, reflected at all angles within the hemisphere bounded by the plane of the specimen, to the flux reflected from a perfect reflecting diffuser under the same geometric and spectral conditions of measurement, *e.g.* under diffuse illumination by a D65 standard illuminant which provides uniform illuminance (lux/m) onto the sample.

In a further embodiment, the request on the dark and uniform appearance of the first emitting surface 28 far from direction 32 is even more stringent, since it is required that reflected light is always upper bounded by direct light both for what concerns the absolute luminance value and its fluctuations. More precisely, the embodiment ensures that the first emitting surface 28 preserves the same characteristics in terms of the background light also as a passive optical element, *i.e.* with respect to light that it reflects and diffuses when it is made to operate inside a fairly luminous environment. In other terms, the direct-light source 12 guarantees dark and uniform appearance for any polar angle of observation outside the emitting cone 30 also in the presence of strong ambient light.

The request could be translated in saying that the direct-light source 12 should be configured such that, when the diffused-light generator 10 is removed from the artificial illumination device and the direct-light source 12 is off and the first emitting surface 28 is illuminated by an external diffused light which delivers onto the first emitting surface 28 a constant illuminance equal to the average of the illuminance delivered by the direct-light source 12 itself onto the first emitting surface when it is on, the external diffused light is reflected or backscattered by the light-emitting surface producing a reflectance luminance profile L_R at the first emitting surface 28 which is weaker than L_{direct} at any position and any angle within at last 90% of the first emitting surface 28, and wherein L_R exhibits an amplitude standard deviation within any 10 mm diameter spatial circular area that lower than the corresponding standard deviations of L_{direct} within at last 90% of the first emitting surface 28.

In formulas, the aforementioned constraints on the “weakness” and “uniformity” of L_R, read:

$$L_R(x,y,\vartheta,\varphi) < L_{direct}(x,y,\vartheta,\varphi)$$

for all x, y $\in A_{90\%}$, all $\varphi \in [0;2\pi[$ and all $\vartheta \in [0,\pi]$

$$\underset{x,y}{\sigma}\left(L_R(x,y)\big|_{\vartheta,\varphi}\right) \leq \underset{x,y}{\sigma}\left(L_{direct}(x,y)\big|_{\vartheta,\varphi}\right),$$

for $(x,y) \in A_{10\,mm}(X,Y)$ all $\varphi \in [0;2\pi[$ and all $\vartheta \in [0,\pi]$

wherein all $(X,Y) \in A_{90\%}$
with $A_{90\%}$ denoting a portion taking up 90% of the whole area of the first emitting surface 28 which portion may be simply connected or not, A_{10mm} denoting any circular area of 10 mm diameter at (X;Y) within A, $\underset{x,y}{\sigma}$ denoting the standard deviation of the argument with respect to the spatial coordinates, and wherein
$L_R(\vartheta,\varphi)\big|_{x,y} = L_R(x',y',\vartheta,\varphi)$ for $x' = x, y' = y$

In a different embodiment, the constraints on the spatial fluctuations in the direction and the width of the peak 30 of light generated by the direct-light source 12 at the first emitting surface 28 are formulated differently, namely the luminance profile L_{direct} shows a range of a distribution of a local direction of a maximum value over the first emitting surface 28, of less than 2°, and the mean value over the first emitting surface 28 of a HWHM of a local average polar angle profile of L_{direct} averaged over all azimuthal angles is below 5°. Expressed in terms of formulas, this means:

$$\max_{x,y}\left(\arg\max_{\vartheta} L_{direct}(\vartheta,\varphi)\Big|_{x,y}\right)\leq 2^{\circ} \text{ for all x, y } \in A_{90\%}$$

$$\mu_{x,y}\left(\underset{\vartheta}{HWHM}\left(\frac{1}{2\pi}\int_{\varphi\in[0;2\pi[} L_{direct}(\vartheta,\varphi)\Big|_{x,y}\, d\varphi\right)\right) < 5^{\circ} \text{ for all x, y } \in A_{90\%}$$

wherein

$$L_{local\ \max}\Big|_{x,y} \equiv \max_{\vartheta,\varphi} L_{direct}(\vartheta,\varphi)\Big|_{x,y}$$ (*i.e.* maximum luminance at given position) and

$$\arg\max_{\vartheta} L_{direct}(\vartheta,\varphi)\Big|_{x,y} \equiv \left\{\vartheta \,\Big|\, \exists\, \varphi \,\Big|\, L_{direct}(\vartheta,\varphi)\Big|_{x,y} = L_{local\ \max}\Big|_{x,y}\right\}$$ (*i.e.* polar angle at which said maximum luminance at given position occurs)

and wherein

$$L_{direct}(\vartheta,\varphi)\Big|_{x,y} = L_{direct}(x',y',\vartheta,\varphi) \text{ for } x'=x,\ y'=y$$

Naturally, the distribution of the direction of the maximum value of the luminance profile should differ from a radially symmetric vector field so that shadows cast by objects in the direct light are not aligned along converging directions More precisely, the direct-light source is configured such that a plurality of elongated objects that are lit by the direct-light source and are oriented along direction 32 and parallel to each other cast onto an arbitrary plane a plurality of shadows that should not be featured by radially symmetric outwardly pointing behavior which is typical for illumination by a localized source at finite distance. To this end, the spatial fluctuations in the direction of the peak 30, which may occur within the limitation of above, may be irregular or random.

By combining the direct-light source 12 and the diffused-light generator 10 in any of the manners described above, the sun-sky imitating device, which is configured as an artificial illumination device 20, provides a luminous, preferably bluish background that mimics the sky and stems from the diffused-light generator 10, while light caused by the direct-light source 12 which leads to the bright spot is warmer in CCT. When walking in front of the first emitting surface 28, this spot moves across it as the sun would across a real window.

Notably, once the direct light of the direct-light source 12 is seen by the observer with both eyes, the observer will perceive the bright spot at infinite distance. In particular, this will be the case if L_{direct} is independent from x, y and φ and virtually null for $\vartheta > \vartheta_0$ and has a constant value for $\vartheta < \vartheta_0$, where ϑ_0 is, for example, 3° or more preferably 1° or even more preferably 0.5°. However, some discrepancy from this ideal regime is obviously acceptable as the above examples for possible constraints showed. The amount of acceptable discrepancy is mainly dictated by the need of guaranteeing the above-mentioned large (virtually infinite) depth perception to occur in absence of visual perception conflicts, or at least in absence of conflicts which lead to a prevailing depth perception at finite distance. This condition is ensured by the above examples for possible constraints.

The visibility of the real image of direct-light source at finite distance translates into a given contribution to the luminance profile L_{direct}, which therefore should be within some limit in order not to spoil the depth effect. In other terms, if the above listed ideal constraints on L_{direct} are fulfilled, the direct-light source 12 is not visible, the only visible object being the bright spot. In order to clarify the acceptable discrepancy, one should account that the observer easily perceives very weak spatial variations on the object luminance as well as color distribution, provided that the angular frequency is not larger than the limit imposed by the eye resolution, *i.e.* 0.07°. This means that assuming a minimum distance of the observer from the device 20 of 1 meter, for example, spatial variations of the direct-light source 12 are acceptable providing that they occur on a scale smaller than approximately 1mm. The occurrence of luminance variation over large scale can be easily spotted by the eyes of the observer, at least if it occurs for $\vartheta > \vartheta_0$, where the vision is not saturated.

It is noticed that a background luminance of 10% of the maximum is a very high figure, which might, however, be acceptable in certain conditions such as conditions aimed at reproducing the sky and sun illumination at the very sunrise or sunset, *i.e.* when the luminance of the sun is not as high with respect to the luminance of the sky as during day time.

A further embodiment for the direct-light source 12 could even be construed, if the following constraints could be fulfilled by the light emitting devices (LEDs):

(i) The size of each LED (including the lens dome) in the direction perpendicular to the emission direction would have to be substantially reduced, *i.e.* it should be reduced down to 3mm, preferably 1mm, most preferably 0.5mm. This would obey the uniformity constraint both in the on and off mode.

(ii) The ratio between the size of the LED emitter, *i.e.* the size of the phosphor or dye zone, *i.e.* its linear dimension which is typically about 1 mm for the smallest currently available general lighting LEDs, and the dome lens focal length, should be about 1/10 to 1/50 in order to guarantee divergences in the range of 1° to 5°. By considering for example 1° divergence and assuming a focal length of 1 mm and a dome diameter comparable to the focal length as would be needed to ensure maximum throughput, one would end up with LED emitter sizes below 20 μm.

(iii) Moreover, each LED emitter and its associated dome should be embedded into a micro dark box. This box should be covered by an absorber which substantially absorbs all the ambient light which crosses the dome lens apart from the ambient light which returns onto the LED emitter. In this case, the LED matrix would appear dark when lit by external light. Moreover, it should avoid scattered light from the surrounding of the LED (*e.g.* from the LED board) to be coupled with the lens dome.

(iv) The LED dome lenses could be antireflection coated in order to minimize reflection of ambient light back to the ambient.

Summarizing the above, the direct-light source 12 could be construed such that it comprises a 2-dimensional array of LEDs of special structure set out in more detail herein below with respect to Fig. 2. In particular, each of LEDs 44 comprise a light emitter 46, such as a light emitting diode comprising phosphor and/or dye or the like and a collimator, *e.g.* a dome lens 48, wherein the dome is positioned at a distance 49 from the light emitter 46 substantially equal to the dome focal length. Preferably, the light emitters 46 have a circular cross section in a plane perpendicular to direction 32, in order to facilitate the achievement of a luminance distribution independent of the azimuthal coordinate. All internal surfaces of domes 48, but the windows 52 at the upstream side thereof through which the light emitters 46 emit their light, and the downstream ends thereof where the light collimating lens surfaces 54 are formed, are covered by a light absorber so as to form micro dark boxes as indicated at 56. As just described, surface 54 may be antireflection coated and the lateral dimension or width of the light emitting zones of the light emitters 46, *i.e.* 58, should be small enough so that the ratio between width 58 on the one hand and length 49 on the other hand is smaller than 1/10, preferably smaller than 1/20, most preferably smaller than 1/50. Additionally, pitch 50 should be smaller than 3 mm, preferably 1 mm, most preferably 0.5 mm. As mentioned before, the LEDs 44 may be packed closely such as in a hexagonal manner. The array of LEDs 44 would cover an area as wide as the first emitting surface 28.

Fig. 4, for example, shows the direct-light source 12 as comprising a first light-emitting device 60 configured to emit primary light 62 and a collimator in the shape of a collimating lens 64 positioned downstream to, and at a focal distance 66 from, the first light-emitting device along an optical axis 68 which coincides with the direct-light direction 32. Differently from standard lighting devices, *e.g.* the case of the LED dome lens featuring the embodiments of Fig. 28, in the present embodiment the lens 64 may be an imaging optical component, in the sense that the lens quality with respect to the given optical lay out parameters (*i.e.* the system numerical aperture, the distance between lens and emitting device, the ratio between focal length and transverse size of the emitting device, *etc.*) may be such as to ensure the lens to perform an image of the first light-emitting device 60 at infinity.

In order to achieve lower fabrication costs and structural compactness, the collimating lens 64 may be a Fresnel lens. The first light-emitting device 60, in turn, may be embodied as an LED.

With regard to the description of Fig. 4, it should be noted that the optical axis 68 may coincide with the optical axis of the collimating lens 64 or may be oblique thereto with the optical axis 68 then being defined by a line connecting the intersection 61 between the collimating lens' 64 principal plane (in case of two principal planes, the one positioned nearer to the first light-emitting device 60) and the lens' 64 optical axis, with a barycenter of the first light-emitting device's 60 light emitting zone. In the case of Fresnel lens 64, the Fresnel lens 64 may be oriented in parallel to the first emitting surface 28 or may lie within the same as further outlined below. In case of other collimating lenses 64, the same may apply for the principal plane. In any case, the lens' 64 aperture covers an area as wide as the first emitting surface 28.

The first light-emitting device 60 may have a circular aperture so as to result in a circular shape of the bright spot 40, in the observer's eyes focused at infinity.

As also shown in Fig. 4, the direct-light source 12 of Fig. 4 may additionally comprise an absorber forming a dark box 70 housing the first light-emitting device 60 and having an aperture where the collimating lens 64 is positioned, wherein an internal surface 72 of the dark box 70 is formed by a light absorbing material having an absorption coefficient for visible light greater than 70%, preferably 90%, more preferably 95%. This results in obeying the reflectance luminance angular profile constraints.

It should be noted that Fig. 4 is illustrative with respect to many features and could be varied accordingly. For example, the collimating lens' 64 aperture does not need to be circular as depicted in Fig. 4. Alternatively, it may be rectangular, hexagonal or have some other polygonal shape. With respect to the shape of the dark box 70 and its internal surface 72, it should be noted that same does not need to be cylindrical with a top face coinciding with the collimating lens' 64 aperture and the first light-emitting device 60 being integrated into an aperture of the bottom face of the cylinder or positioned within the cylinder. Any other shape may also be valid as long as any direct light paths between the first light-emitting device 60 and the collimating lens' 64 aperture is left unblocked. For example, the internal surface 72 could extend between the cylinder shown in Fig. 4 and the frustum being non-concave, having minimum volume and extending between the light emitting zone of first light-emitting device 60 on the one hand and the aperture of the collimating lens 64 on the other hand.

In order to fulfill the above outlined possible constraints regarding the luminance profile L_{direct}, the ratio between the focal length 66 of collimating lens 64 on the one hand and the width 74 of the first light-emitting device's 60 aperture may be greater than 10 and preferably greater than 50. The focal length 66 may, for example, be greater than 10 cm and preferably greater than 20 cm. The area of the collimating lens' 64 aperture may, for example, be greater than 80 cm^2 and preferably greater than 300 cm^2. The downstream face of collimating lens 64 may form the light-emitting surface.

With respect to the values presented regarding the embodiments of Figs. 2 to 4, it should be noted that the values presented for these embodiments with regard to for example the ratio between the focal length and the light emitting aperture, do not need to result in a complete obedience of the previously outlined constraints regarding the luminance profile. Rather, the embodiments of Figs. 2 to 4 may be combined, for example, with subsequently described embodiments for micro-optics beam-homogenizer layer so as to fulfill the constraints. Accordingly, embodiments of Figs. 2 to 4 may also form merely a part of the direct-light source 12, namely a collimated light source for generating pre-collimated light, *e.g.* a light beam with limited HWHM angular divergence (for example with HWHM angular divergence smaller than 2.5°) but featured by the presence of stray light at larger angles, as for example stray light leading to secondary peaks or spikes in the light-beam angular profile.

In any case, for a typical size of the Fresnel lens 64 of about 20cm and for a typical distance between the lens 64 and the observer of about 1.5m the configuration of Fig. 4 results in the angular divergence of the virtual image of the first light-emitting device 60 being smaller than the angular aperture with respect to the observer of the collimating lens 64, thereby ensuring that the image of the bright spot 40, *i.e.* the image of the first light-emitting device 60, appears as a luminous dot beyond the collimating lens' 64 aperture. That is, the image of the sun appears smaller than the aperture of lens 64 and the lens 64 itself is interpreted as a transparent window between the eye and the virtually distant object 40. An advantage of using a Fresnel lens as lens 64 is the technical possibility of achieving smaller output divergence angles. As an example, typical divergence angles of combinations of LEDs plus TIR lenses, for example, are of the order or larger than 8° to 10°. One of the main limits is due to the focal distance of the optical element, *i.e.* the TIR lens, which is of the order or less than 1 to 5 cm. In the case of the Fresnel lens, the focal length of such a lens may be of the order of 20 to 30 cm, for example. The output angular divergence is thus given by the ratio between the spatial aperture 74 of the first light-emitting device 60 (including or not including a primary optics element, such as an LED dome) and the above mentioned focal length 66. For a 1 to 2 mm LED as an example for the first light-emitting device 60, and a focal length of 20 to 30 cm, the divergence is of the order or lower than 1°.

A further advantage of the configuration of Fig. 4 is the absence of pixelation of the sun image.

As shown in Fig. 5, pairs of first light-emitting devices 60 and lenses 64 may be combined together and positioned in juxtaposition so that the collimating lenses 64 of the pairs abut each other so as to form a joined continuous surface. If the collimating lenses 64 are formed as Fresnel lenses as illustrated in Fig. 5 by circular lines within one of the lenses 64, then the array of Fresnel lenses may be easily formed by one continuous monolithic object such as plastic or glass. The pairs of first light-emitting devices 60 and collimating lenses 64 may be packed together along the 2-dimensional array of pairs in a hexagonal manner. Accordingly, the apertures of the individual collimating lenses 64 may be formed hexagonally. The optical axis 68 of the individual pairs of device 60 and lens 64 can be arranged to extend parallel to each other and the direct-light direction 32, respectively. The downstream face of lenses 64 could form the first emitting surface 28 or have, at least, an area being as great as the surface 28.

That is, in the case of Fig. 5, the direct-light source 12 comprises a 2-dimensional array of first light-emitting devices 60 which may comprise a circular aperture in order to provide for a circular appearance of a spot, a 2-dimensional array of collimating lenses 64, which are advantageously formed as Fresnel lenses, wherein the two arrays are registered to each other so that the optical axes 68 are parallel to each other and parallel to the direct-light direction 32. The array of lenses and the array of first light-emitting devices may be displaced relative to each other such that the optical axes of the lenses 64 are offset from the positions of the first light-emitting devices so as to result in a direct-light direction 32 which is oblique relative to the plane within which the apertures of lenses 64 are positioned and distributed, respectively.

As already described above, by placing each collimating lens 64 at a distance from the first light-emitting device 60, which corresponds to, or is of the order of, the focal length of the collimating lenses 64, it is possible to achieve the low divergence constraint previously formulated. Notably, the collimating lenses 64 make with the eye lens of the observer a telescope which forms the first light-emitting device and its aperture, respectively, onto the retina. This is the reason why each first light-emitting device should have a circular aperture in order to form a circular image in the observer's eye, *i.e.* form the roundness of a spot.

So far, the embodiments for direct-light source 12 showed the actual light emitting zone to be positioned downstream relative to some collimating lens along an optical axis coinciding with a direct-light direction. The embodiments outlined further below show that the direct-light source 12 may comprise an edge-illuminated lightguide emitter panel comprising a wave guiding panel, operated via total internal reflection, one or more light source(s) coupled to an edge of the wave guiding panel, and a plurality of micro-optical elements such as microprisms, microlenses, etc. which contribute in extracting the light from the wave guiding panel into the direct-light direction. Thus, while the embodiments of Figs. 2 to 5 could be called "back-illuminated emitters", the embodiments further outlined with respect to the following figures are termed "edge-illuminated lightguide emitter panels".

Fig. 6 shows an embodiment for an edge-illuminated lightguide emitter panel as an example for the direct-light source 12 according to which same comprises a wedge-shaped lightguide layer 80 sandwiched between an absorber shaped as a light absorbing layer 82 and a light exit layer 84 so that the wedge-shaped lightguide layer guides light by total internal reflection and so that the light absorbing layer 82 is positioned upstream relative to the wedge shaped layer 80 and the light exit layer 84 is positioned downstream relative to the wedge shaped lightguide layer 80, wherein $n_3 < n_2 < n_1$ with n_1 being the refractive index of the wedge shaped lightguide layer 80, and n_2 being the refractive index of the light exit layer 84 and n_3 being the refractive index of the light absorbing layer 82. As to layers 80 and 84, they may be made of glass or transparent plastics, while several possibilities exist to realize the light absorbing layer 82. The wedge-shaped layer 80 may feature a wedge-slope below 1 degree. As illustrated in Fig. 6 at 86, the light absorbing layer 82 may actually be a light absorbing panel 88 separated from the wedge shaped lightguide layer 80 via a gap 90 filled, for example, with air, vacuum or another low refractive index material, the refractive index of which is denoted by n_3. Another possibility would be to form the light absorbing layer 82 by some coating, the coating being composed of material having the refractive index n_3 small enough in order to be lower than n_1 and n_2, concurrently. The light-absorbing layer 82 may absorb at least 70%, preferably 90%, most preferably 95% of the visible light which impinges on the light-absorbing layer 82.

As shown in a magnified section 92, the light exit layer 84 comprises a plurality of micro-reflectors 94 at an interface 96 between the light exit layer 84 and the wedge shaped lightguide layer 80 so as to redirect light rays 98 having crossed the interface 96 between the wedge shaped lightguide layer 80 and the light exit layer 84 and propagating at an angle with respect to a normal to an upper (or external) surface 118 of the exit layer which is lower than a limit angle for total internal reflection at said upper surface, wherein said upper surface is a surface of the exit layer facing away from the wedge layer, so that the light reflected by the micro-reflectors propagates out of the light-exit layer into the direct light direction 32.

To be more precise, Fig. 6 exemplarily shows a light ray propagating by internal reflection through the wedge shaped lightguide layer 80 along a guiding direction 106, *i.e.* the direction of gradient along which the wedge shaped lightguide layer 80 gets thinner, which intersects the interface 96 at a point 97 where the angle of the light ray with respect to the normal to the interface 96 is slightly less than the limit angle for total internal reflection. This allows a portion of the light to cross interface 96 and to propagate further at a small angle relative to interface 96 along guiding direction 106, such as ray 98. The micro-reflectors 94 protrude from the interface 96 away from wedge shaped lightguide layer 80 and have reflective surfaces 102 oriented such that reflection of ray 98 points, after refraction from the upper surface 118, into the direct-light direction 32. Accordingly, as shown in at 104, the micro-reflectors 94 may be formed translatory invariant or longitudinally along a direction 99 laying in the plane of interface 96 and perpendicular to the direction of gradient 106, with their face 102 facing upstream relative to this guiding direction 106 being oriented for example at approximately 40° to 50° relative to interface 96 in order to achieve a direct-light direction 32 nearby the normal direction of interface 96. In particular, the micro-reflectors may, for example, be formed as grooves or voids in the material of the light exit layer 84, at the face of this layer 84 forming the interface 96 with the wedge shaped lightguide layer 80. However, other possibilities do exist, too. In other words, the edge illuminated lightguide emitter panel of Fig. 6 comprises a three-layer structure (TLS). The central layer 80 has a wedge shape and is made of a transparent material of refractive index n_1. The bottom layer has refractive index $n_3 < n_1$ and is made to absorb visible light which eventually enters the TLS structure from the upper surface 118 of layer 84, *e.g.* ambient light or light backscattered by the diffused-light generator 10. The upper layer 84 is transparent, has refractive index n_2 fulfilling $n_3 < n_2 < n_1$ and comprises micro-optical elements such as void microprisms for extraction of the light out of the TLS.

The direct-light source 12 of Fig. 9 further comprises an edge illuminator 108 configured to couple light into the wedge shaped lightguide layer 80 from an edge 110 thereof into the guiding direction 106. The edge illuminator 108 comprises a light concentrator 112 such as a reflective concentrator and a first light-emitting device in the shape of light source 114. The combination of the concentrator 112 and the light source 114 generates light collimated in a first plane determined by directions 106 and 99 and in a second plane containing guiding direction 106 and the normal to surface 118. The collimation in the first plane may be stronger than the one in the second plane. Such a concentrating device may be shaped for example as a rectangular compound parabolic concentrator (CPC), as depicted in Fig. 6, which comprises a rectangular input aperture IN that is coupled to the LED source and a rectangular output aperture OUT that faces the input facet of the lightguide 110 and comprises four parabolic mirror surfaces each of which is one-dimensionally curved and has a generator parabola lying either in the first or in the second plane, and with all the generating parabolas having their focus in the plane of the input aperture IN. For example, the input aperture IN is shaped as a thin rectangle elongated along the normal to the first plane. Light source 114 may be formed by a 1-dimensional array of first light-emitting devices 111 such as LEDs and the same applies for concentrator 112 in the sense that a 1-dimensional array 109 of pairs of first light-emitting devices 111 and light concentrators 113 such as reflective ones, could be used as edge illuminator 108.

For what concerns the optical operating principles of the embodiment described in Fig. 6, it is noticed that the collimation in the first plane being stronger than in the second plane is useful for guaranteeing the beam exiting the surface 118 to feature similar divergence in a third plane, containing the directions 32 and 106, and in a fourth plane, containing the directions 32 and 99. In fact, the light extraction mechanism here described may perform a substantial reduction of the beam divergence in the plane of incidence of light rays onto the interface 96, but not in orthogonal planes. The combination of layers 80 and 84 behaves as a collimator, which reduces the beam divergence in said plane of incidence of light rays onto the interface 96, and therefore further contributes to the action of the collimating optics 112 to minimize the divergence of the output beam. When the collimating optics 112 couples the light generated by the primary source 114, such as white light, into the wedge shaped lightguide layer 80, the light rays 100 strike and are initially reflected by total internal reflection by the lower surface 116 of layer 80 facing the light absorbing layer 82 and interface 96 facing layer 84.

The value n_1/n_2 should be chosen large enough to guarantee the coupling for the chosen input light divergence as determined by the combination of primary source 114 and concentrator 112. Owing to the wedge structure of the wedge shaped lightguide layer 80, the light beam divergence increases with propagation inside the lightguide layer 80 along propagation guiding direction 106, leading to continuous leakage from layer 80 to layer 84 when crossing interface 96. Notably, for a proper selection of the refractive index values no leakage occurs at the interface between the central and the bottom zone, namely if $n_1/n_2 < n_1/n_3$. The light that has crossed the interface 96 between layer 80 and layer 84 propagates in the light exit layer 84 almost parallel to interface 96, *i.e.* at a small grazing angle which is, for example, lower than 5° with respect to interface 96. This light could hit the upper surface 118 of layer 84 facing away from layer 80, experience total internal reflection and then cross the interface 96 between layer 80 and layer 84 again. Alternatively, however, light 98 hits one of the micro reflectors 94, thereby being reflected outside the TLS into direction 32. The reflective surface facet of the micro reflectors 84 pointing into the direction of edge illuminator 108 are oriented such that the normal direction of these reflection surfaces 102 are angled relative to the interface 96 at an angle relative to interface 96 corresponding to half the angle which direction 32 encloses with interface 96, plus the aforementioned grazing angle of rays 98. In other words, the angle has to be chosen according to the desired output angle direction 32. In fact, the micro reflectors 84 may be formed as microprisms, and in particular these prisms may be made as void prisms as already outlined above and illustrated at 104. Those void prisms would reflect the light via total internal reflection. Alternatively, the micro reflectors may be mirror coated indentations of the light exit layer 84. All micro-reflectors 94 may be arranged in parallel to each other and may have the same apex angle in order to achieve a constant output direction 32.

The size and the number per unit area of the micro-reflectors 94, *i.e.* their density, may change across the TSL, *i.e.* along the guiding direction 106, in order to optimize the luminance uniformity, *i.e.* in order to obey the above outlined luminance uniformity request.

The divergence of the light beam exiting the surface 118 in the third plane decreases with decreasing input divergence of the edge illuminator 108 in the second plane on the one hand and the wedge slope on the other hand. For example, for $n_1/n_2 = 1.0076$, leading to a lightguide 80 that supports an internal mode of about 14°, and for a wedge slope of 0.5°, the output divergence of the light exiting the TLS in direction 32 in the just mentioned third plane is about 2.25° HWHM. Alternatively, $1.001 < n_1/n_2 < 1.1$ may hold true, for example. For the embodiment described in Fig. 9, the output divergence in the orthogonal plane, *i.e.* in the fourth plane, is basically identical to the input divergence in the first plane. Notably, the output divergences in the two just mentioned orthogonal planes are independent from each other, and the output angular spectrum or luminance angular profile L_{direct} would likely show a rectangular peak into direction 32. A square spectrum could be obtained by suitably choosing the ratio between the input divergence in the first and second plane. The desired roundness in the light source image appearance, *i.e.* a round appearance of a spot, may be achieved by adding a low-angle white-light diffuser such as a “Lee filter 253 Hampshire Forst”, or a “Lee filter 750 Durham Frost” downstream the TLS shown in Fig. 6, as it is described herein below. As it is known, a low-angle white-light diffuser is a diffuser which operates by performing the convolution of the angular spectrum of the impinging light with a given response function, which is here taken symmetric around a certain direction (*e.g.* a normal to a surface of the low-angle white-light diffuser) and having a HWHM divergence less than 10°, preferably less than 5°, more preferably less than 2°.

A solution alternative to the usage of the edge illuminator 108 for the purpose of obtaining a collimation in the first plane stronger than in the second plane may be also obtained by using an array of LEDs configured in such a way to deliver two different divergence values in two orthogonal planes containing direction 32. For example, HWHM divergence of 2.25° and 20° in the two planes may be obtained using rectangular LED emitters 46 of size $0.31 \cdot 2.8\text{mm}^2$ and a lens dome with focal length (distance 49) of about 4mm.

The fact that the light absorbing layer 82 of the TLS is light absorbing ensures the black appearance of the direct-light source 12 when the same is off, thereby fulfilling the above outlined constraints regarding the reflectance luminance profile, *i.e.* the low luminance value outside the emission cone. In fact, the light absorbing layer’s interface to layer 80 behaves as a mirror only for the light guided inside the lightguide layer 80, but is virtually transparent for the light coming from outside the TLS, *i.e.* such as the aforementioned diffused light entering the light-emitting surface of the direct-light source 12 from outside. Such light is then for example absorbed by the light absorbing panel 88.

Fig. 7 shows another example for an implementation of the direct-light source 12 in the form of an edge illuminated lightguide emitter. Here, the edge illuminated lightguide emitter panel comprises a light guide layer 120 sandwiched between an absorber shaped as a light absorbing layer 122 and a light exit layer 124 so that the light absorbing layer 122 is positioned upstream relative to light guide layer 120 and the light exit layer 124 is positioned downstream relative to the light guide layer 120. With regard to possible implementations of layers 120, 122 and 124, reference is made to the description of Fig. 6. However, there is a greater freedom in choosing the refractive indices of layers 120 to 124. In particular, $n_3 < n_1$ and $n_2 < n_1$ is sufficient with n_1 being the refractive index of the light guide layer 120, n_2 being the refractive index of the light exit layer 124, and n_3 being the refractive index of the light absorbing layer 122, which may comprise a transparent gap as described for the layer 82 of Fig. 6. The light guide layer 120 comprises a plurality of micro-reflectors 126 at an interface 128 between the light absorbing layer 122 and the light guide layer 120 so as to redirect light internally guided within the light guide layer 120 toward the light exit layer 124 at an angle with respect to the normal to the interface 134 between layer 120 and 124 which is smaller than the limit angle for total internal reflection for the light guided within layer 120. Each micro-reflector 126 is positioned at a focal point of a respective lens 130 formed on an outer surface 132 of the light exit layer 124 facing away from the light guide layer 120. The combination of the micro-reflector 126 and lens 130 arrays thus constitutes a collimator to reduce the divergence of the output light.

Other than the embodiment of Fig. 6, the configuration of the edge illuminated lightguide emitter panel of Fig. 7 is based on a rectangular light guide layer 120, *i.e.* the light guide layer 120 has parallel interfaces to layers 122 and 124, respectively, namely interface 128 to light absorbing layer 122, and interface 134 to light exit layer 124. The micro-reflectors 126 and the collimating lens formed at the outer surface of the light exit layer 124 are 2-dimensionally distributed along the interface 128 and the outer surface 132, respectively, and registered to each other so that the optical axis 135 extending through each micro-reflector 126 and the respective collimating lens 130 are parallel to each other and the direct-light direction 32, respectively. Further, an edge illuminator 108 couples light into an edge 136 of the light guide layer 120, wherein as shown in Fig. 7 this edge illuminator 108 may also be composed of a 1-dimensional array of pairs of a first light-emitting device 138 and corresponding concentrator 140 extending 1-dimensionally along the edge 136 just as illustrated in Fig. 6.

That is, each micro-reflector 126 faces a corresponding one of the collimating lenses 130, both being positioned at a focal distance from each other. The micro-reflectors 126 have an elliptic mirror face oriented so as to mirror light coupled into the light guide layer 120 along a central propagation direction 142 (*i.e.* the direction along which the lightguide is illuminated), into the direction 32, *i.e.* along optical axis 135. In particular, the shape of the micro-reflectors 126 may be that of a cylinder protruding from interface 128 and being cut at the just mentioned mirror angle, *i.e.* the angle necessary in order to lead to a circular cross section when projected onto a plane orthogonal to direction 32. This circumstance ensures circular output angular spectrum, and thus the visual appearance of a round source or spot 40. The ratio between the lenses' focal length and reflectors' size/width measured in the just mentioned plane orthogonal to direction 32, for example as indicated at 144 in Fig. 7 for the case of direction 32 perpendicular to surface 134, defines the output FWHM angular spectrum or luminance profile L_{direct} and therefore has, for example, a value in the range of 10 to 100, depending on the desired divergence. For example, reflectors 126 with diameters 144 of 100 micron and lenses of 3 mm focal length 146, wherein the focal length is defined in the refractive layers 120 and 124, lead to about 1.5° divergence HWHM downstream the surface 132, wherein refractive index of layers 120 and 124 are assumed to have value about 1.5 and propagation in air is assumed downstream layer 124. The size of the lenses 130 is determined by the need of capturing the light reflected by the micro-reflectors. For example, it can be taken 1.5 times the product between the focal length 146 and 2 times the tangent of the internal lightguide mode half divergence, which means a lens diameter 148 of the order of one half of the focal length for a lightguide coupling 2x10° internal divergence mode. The lateral distribution or density of the 2-dimensional distribution of the reflector/lens-coupler pairs should be tailored in order to maximize luminance uniformity, averaged over an area of few-lens diameter. The lenses 130 may be formed on the material of layer 124 featuring a flat interface 134 with the lightguide layer 120 and a lower refractive index. In doing so, the lenses 130 do not interfere with the lightguide 120 and operate only on that light which is reflected by the micro-reflectors 126 so as to exit the first emitting surface 28 in direction 32.

Some of the embodiments for the direct-light source outlined above may show spatial luminance modulation over the first emitting surface 28. Exemplary embodiments to address any influence of those spatial luminance modulation can be taken from WO 2014/075721 A1 mentioned above such as a coffered ceiling structure or the use of freeform lenses or reflective compound parabolic concentrators. Freeform lenses may achieve one or possibly most of the previous requirements such as uniform illumination.

Moreover, embodiments may comprise micro-optics beam-homogenizer layers as described in WO 2014/075721 A1 mentioned above positioned downstream the collimated light source and potentially upstream the diffused-light generator. Micro-optics beam-homogenizer layers are able to transform a first collimated beam featured by the presence of stray light into a second collimated beam with divergence equal to or larger than the divergence of the first collimated beam and which is free from stray light. Such second collimated beam thus exit the first emitting surface 28, e. g., towards the diffused-light generator.

All of the above described embodiments for the direct-light source 12 may be extended by additionally providing the direct-light source 12 of the artificial illumination device 20 with a low-angle white-light diffuser 230 which is, as shown in Figs. 8 and 9, positioned either upstream or downstream of the diffused-light generator 10. In case of positioning the low-angle white-light diffuser 230 upstream the diffused-light generator 10, the latter is external and downstream the direct-light source 12 as shown in Fig. 8. In the other case, *i.e.* if the low-angle white-light diffuser 230 is positioned downstream the diffused-light generator 10, then the low-angle white-light diffuser 230 represents a device residing within, and positioned within the internal light path of the direct-light source 12. In both cases, the first emitting surface 28 of the direct-light source 12 is formed at the low-angle white-light diffuser 230, namely its outer face. In case of Fig. 9, however, $L_{direct}(x, y, \vartheta, \varphi)$ is intended to denote the luminance measurable at the low-angle white-light diffuser 230 outer surface (*i.e.* the surface 28 facing in the opposite direction with respect to diffused-light generator 10) when the diffused-light generator 10 is physically removed from the illumination device 20. In Fig. 9, the reference sign 12' has been used to identify the portion of the direct-light source 12 positioned upstream relative to the diffuse-light generator 10. Both parts 12' and 230 belong to the direct-light source 12 as indicated by the brace in Fig. 9. As far as the reflectance luminance profile L_R is concerned, same may be defined with the diffused-light generator 10 remaining within the direct-light source 12 in case of Fig. 9. For example, the low-angle white-light diffuser 230 is configured so as to cause a blurring of the narrow peak 30 in L_{direct}. Such blurring occurs both when the white-light diffuser 230 is positioned upstream and downstream of the diffused-light generator 10.

The low-angle white-light diffuser 230 may comprise, for example, a random distribution of micro-refractors, *e.g.* micro-lenses, micro-voids, micro-prisms, micro-scratches, or a combination of these, formed in an outer surface of a transparent layer material, or a dispersion of transparent microparticles in a transparent bulk material where particles and bulk material experience suitable refractive-index mismatch. That is, in the case of the dispersion of transparent microparticles in a transparent bulk material, a refractive-index mismatch between the transparent microparticles and the transparent bulk material may apply. However, several other embodiments for the white-light diffuser are also possible.

Note that, since light rays impinging onto the low-angle white-light diffuser may experience only small-angle deviation (*e.g.* smaller than 2.5°), a small-angle white-light diffuser is typically a virtually transparent element according to the definition of transparency taken in the context of the present invention (an element is considered as transparent if light rays crosses the element without experiencing angular deviation larger than 2.5°; see below for details). Accordingly, rays that cross the diffuser suffering a small angle deviation are here considered as transmitted rays (see below for details). However, according to the needed functionality, the small-angle white-light diffuser that is here considered should typically ensure that most of the transmitted rays (*e.g.* at least 50%, preferably 70%, most preferably more than 95%) experience at least some angular deviation (*e.g.* a deviation of at least 0.5°). In other terms, the diffuser should ensure low regular transmittance (*e.g.* a regular transmittance lower than 50%, preferably lower than 30%, most preferably lower than 5%).

The low-angle white-light diffuser 230 may have the following positive effects onto the direct-light luminance profile L_{direct}. In particular, a scattering cross section of this white-light diffuser 230 may be set to 2° to 10°. A first scope is to blur any sharp angular peak in L_{direct} profile, *i.e.* a peak featured by HWHM less than 1.5° -10°, which might occur outside the narrow peak 30. The scope is here therefore to reduce the visibility of sharp secondary angular peaks in L_{direct}. To this end the diffuser may be positioned at any plane downstream the plane where said luminance angular peaks are originated. A second scope is to blur and so reduce both luminance value and its spatial derivative caused by bright, spatially localized, spots, and improve spatial uniformity in the luminance profile. To this end the low-angle white-light diffuser should be positioned at a certain distance from the plane where said luminance spots occurs, in order to allow each localized spot to lead to a sufficiently large and so sufficiently weak blurred spot onto the plane. In so doing, the low-angle white-light diffuser causes a blur in the spatial luminance profile wherein (in the case of negligible regular transmittance) a point is blurred into a blurred spot with radius approximately equal to the product of the tangent of the diffuser angular response and the distance between the original-luminance plane and the diffuser. Naturally, the new blurred luminance profile occurs at the diffuser plane. For example, an observer sees a localized spot of original size *ds* under a luminance reduced by a factor of $\cong \alpha^2$ if a 2.5° HWHM white-light diffuser 230 is positioned downstream said spot at a distance of $\cong 10\alpha \cdot ds$, wherein a proportionally larger distance is necessary for white-light diffusers featured by narrow angular response.

Up to now, the various embodiments of the artificial illumination device 20 that have been presented concerned variations in the implementation of the direct-light source 12.

Within the various concepts disclosed herein, it will be understood that the direct-light source can be used as starting point for a sun-sky imitating device or as a sun imitating device.

Next, possible variations in the implementation of the diffused-light generator 10 are described. The description provided next is combinable with any of the embodiments described above. Although some aspects may primarily relate to sun-sky imitating devices, some aspects may similarly be used in sky imitating devices.

Fig. 10A shows one of the possible general relative arrangements of direct-light source 12 and diffused-light generator 10. The diffused-light generator 10 is arranged downstream relative to the direct-light source 12 in this figure. Possible other relative configurations of these elements have already been described before and will be further discussed in the following. In Fig. 10A the backside of the diffused-light generator 10 is lit by the directed light 236 generated by the direct-light source 12 and the first emitting surface 28. As the diffused-light generator 10, as described above, is at least partially transparent to the directed light 236 or any intermediate light evolving from the primary light and resulting in the directed light 236, a transmitted light portion 238 results at the front face/outer emitting surface 37 of diffused-light generator 10.

Besides this, the diffused-light generator 10 generates diffused light 242. As outlined in more detail below, the diffused-light generator 10 may be configured to generate the diffused light 242 by way of diffusing a portion of an incident light, such as directed light 236 or an intermediate light evolving from the primary light and resulting in the directed light 236, and/or by additionally emitting diffused light as an additional contribution. As already described above, the diffused-light generator 10 may be embodied as a panel, as a layer or layer stack deposited onto, for example, the first emitting surface 28 or some other transparent substrate, but other implementations would also be feasible.

Preferably, the directed light 236 emitted by direct-light source 12 covers the visible region of the spectrum that is wavelengths between 400 nm and 700 nm. Preferably, the spectrum of the directed light 236 has a spectral width $\Delta\lambda$ which is larger than 100 nm, more preferably larger than 200 nm, where the spectral width $\Delta\lambda$ may be defined as the standard deviation of the spectrum of the directed light 236. The spectrum of the directed light 236 thus features an associated CCT value which is called CCT_{direct} in the following.

It is preferred if the diffused-light generator 10 is configured such that same does not increase the CCT of the transmitted light 238, *i.e.* $CCT_{trans} \leq CCT_{direct}$, but deviations could also be feasible. As far as the diffused light 242 is concerned, same has a spectrum shifted towards smaller wavelengths and accordingly has a higher CCT compared to the directed light 236, and in any case a higher CCT than compared to the CCT of the transmitted light 238, *i.e.* $CCT_{diffuse} > CCT_{direct}$ and $CCT_{diffuse} > CCT_{trans}$. It is preferred if light 236 and 238 are collimated, *i.e.* have narrow angular distribution, and if spectra of directed light 236, 242 and 238 are substantially independent from the angular direction (when the spectra are normalized to their peak value). In this case, the definition of CCT_{direct}, $CCT_{diffuse}$ and CCT_{trans} is straightforward. However, to be more precise and in the general case, CCT_{direct} could be defined as the CCT relative to the mean spectrum of light generated by the illumination device 20 within the narrow peak 30, *i.e.* within, for example, ϑ_{HWHM}, when the diffused-light generator 10 is not physically installed into the device 20; CCT_{trans} could be defined as the CCT relative to the mean spectrum of light generated by the illumination device 20 within the narrow peak 30, *i.e.* within, for example, ϑ_{HWHM}, when the diffused-light generator 10 is physically made to operate into the device 20; $CCT_{diffuse}$ could be defined as the CCT relative to the mean spectrum of light generated by the illumination device 20 at directions far from direction 32, *e.g.* for angles $\vartheta > 3\ \vartheta_{HWHM}$, when both direct-light source 12 and diffused-light generator 10 are made to operate into the illumination device 20; all means are preformed over all spatial and azimuthal coordinates.

As already described above, the diffused-light generator 10 could be embodied or could at least comprise a diffuser panel configured to diffuse the incident light more efficiently for shorter wavelengths within the visible region, *i.e.* within 400 to 700 nm, than compared to longer wavelengths, thereby behaving similarly to the Rayleigh scattering of the sunlight by the real sky. For example, the diffuser is configured such that the luminous flux of the portion diffused/scattered by same within the interval of 400 nm to 550 nm is at least 1.1 times, preferably 1.2 times, more preferably 1.3 times larger than the luminous flux of the portion of incident light within the wavelength interval within 550 nm to 700 nm, in the case of a D65 standard illuminant.

$CCT_{diffuse}$ is, for example, at least 1.2 times greater than CCT_{trans}, preferably more than 1.3 times greater, more preferably more than 1.4 times greater. Comparing $CCT_{diffuse}$ with CCT_{direct}, $CCT_{diffuse}$ may be 1.2 times greater than CCT_{direct}, or preferably more than 1.3 times greater or more preferably more than 1.4 times greater.

In case of the just mentioned Rayleigh-like diffuser, the diffuser may also decrease the CCT_{trans} relative to CCT_{direct}, as the transmitted light 238 represents the residual component of the incident light not having been scattered/diffused, not belonging to diffused light 242.

Preferably, the diffused-light generator 10, irrespective of same being a diffuser and/or a diffused-light source (e. g. if the sky imitating device that is configured as an additional diffused-light emitter), does not absorb significant portion of the incident light. Preferably, the diffused-light generator 10 absorbs less than 20% of the luminous flux of the incident light and more preferably less than 10%. In this regard however, it should be mentioned that some of the incident light is scattered or reflected back into the direction pointing away from the input surface 33 in the upstream direction. When comparing the portion of incident light scattered back ion the one hand and the portion of incident light scattered into the forward direction, *i.e.* away from the second emitting surface 34 in the downstream direction, then the transmitted diffused light portion 242 should be preferably greater such as, measured in luminous flux, at least 1.1 times greater or preferably 1.3 times greater or even more preferably 1.5 or even 2 times greater than the back-scattered portion.

As far as the sum of the reflected and back-scattered portion is concerned, *i.e.* the portion of incident light reflected back or scattered back by diffused-light generator 10, same should preferably be lower than 40% of the luminous flux of the incident light and preferably lower than 25% or even lower than 10% or even lower than 5% of the luminous flux of the incident light.

Fig. 11 shows an embodiment where the diffused-light generator 10 is configured as a diffuser 250 comprising a solid matrix of a first material, wherein nanoparticles 254 of a second material are dispersed within the solid matrix 252. The refractive index of the nanoparticles material is different from the refractive index of the material of solid matrix 252. Both materials basically should not absorb electromagnetic radiation in the visible wavelength range. For example, the first material may be a transparent resin. For example, the second material may be an inorganic oxide such as ZnO, TiO_2, ZrO_2, SiO_2, Al_2O_3.

As illustrated herein, scattering aspects are related to a relative refractive index between nanoparticles and a host material. Accordingly, nanoparticles may refer to solid particles as well as optically equivalent liquid or gaseous phase nanoscale elements such as generally liquid or gas phase inclusions (e.g. nanodroplets, nanovoids, nanoinclusion, nanobubbles etc.) having nanometric size and being embedded in the host materials. Exemplary materials that comprise gas phase inclusion (nanovoids/nanopores) in a solid matrix include aerogels that are commonly formed by a 3 dimensional metal oxides (such as silica, alumina, iron oxide) or an organic polymer (e.g. polyacrylates, polystyrenes, polyurethanes, and epoxies) solid framework hosting pores (air/gas inclusions) with dimension in the nanoscale. Exemplary materials that comprise liquid phase inclusions include liquid crystal (LC) phases with nanometric dimensions often referred to as liquid phase including nanodroplets that are confined in a matrix that commonly may have a polymeric nature. In principle, there is a large variety of LCs commercially available, e.g. by Merck KGaA (Germany). Typical classes of liquid crystal may include cyanobiphenyls and fluorinated compounds. Cyanobiphenyls can be mixed with cyanoterphenyls and with various esters. A commercial example of nematic liquid crystals belonging to this class is “E7” (Licrilite® BL001 from Merck KGaA). Furthermore, liquid crystals such as TOTN404 and ROTN-570 are available from other companies such as Hoffman-LaRoche, Switzerland. In this context and regarding potential embodiments of scattering configurations, it is also referred to the above mentioned WO 2017/084756 A1.

The nanoparticles 254 may be mono-dispersed. The nanoparticles 254 may be round shaped or shaped otherwise. The effective diameter D – for definition in non-round cases see below – may be within the range [5 nm-350 nm], preferably [10 nm-250 nm], more preferably [40 nm-180 nm], still more preferably [60 nm-150 nm], where D is given by the diameter of nanoparticles 254 times the first material’s refractive index.

Moreover, nanoparticles 254 may be distributed inside the diffuser 250 so that their number per square meter N, *i.e.* the number of such particles within a panel volume element delimited by a portion of surface S orthogonal to the direction of light propagation and with a 1 m^2 area, satisfies the condition $N_{min} \leq N$, where:

$$N_{\min} = \frac{10^{-29}}{D^6} \cdot \left| \frac{m^2 + 2}{m^2 - 1} \right|^2 \qquad \text{[Number/ m}^2\text{ with } D \text{ expressed in m]}$$

where the effective diameter D must be expressed in meters (dimensional terms are comprised in the constant) and where m is equal to the ratio of the second material’s refractive index to the first material’s refractive index.

Preferably, the nanoparticles 254 are distributed homogenously, at least as far as the areal density is concerned. The areal density varies, for example, by less than 5% or the mean areal density. Alternatively, the areal density may vary intentionally in order to compensate for an illumination variance over the panel 250 as lit the incident light. For example, the areal density $N(x,y)$ at point (x,y) within the second emitting surface 34 may be related to the illuminance $I(x,y)$ produced by the source 2 at point (x,y) via $N(x,y) - N_{av} I_{av} / I(x,y)$+-5%, where N_{av} and I_{av} are the averaged illuminance and areal density over the panel area.

In the limit of small D and small volume fractions (*i.e.* thick panels) an areal density $N \approx N_{\min}$ is expected to produce scattering efficiency of about 5%. As the number of nanoparticles per unit area gets larger, the scattering efficiency is expected to grow proportionally to N, as long as multiple scattering or interferences (in case of high volume fraction) occur, which might compromise color quality. The choice of the number of nanoparticles is thus biased by the search for a compromise between scattering efficiency and desired color, as described in detail in patent application EP2304478. Furthermore, as the size of nanoparticles gets larger, the ratio η of the luminous flux of the forward scattered light 242 divided by the luminous flux of the back-scattered light grows, such ratio being equal to one in the Rayleigh limit. Moreover, as η grows, the aperture of the forward scattering cone gets smaller. Therefore, the choice of η is biased by the search for a compromise between having light scattered at large angles and minimizing the flux of backward scattered light. However, in a way known by itself, an antireflective layer can be deposited on the input and second emitting surface 33 and 34, respectively, with the aim of minimizing reflection; by doing so, the luminous efficiency of the device is raised and the visibility of the diffuser panel 250 to an observer due to ambient reflection on the panel surfaces is diminished.

Embodiments are however possible where nanoparticles 254 do not have spherical shape: in such case, the effective diameter D may be defined to be equal to the effective diameter of the equivalent spherical particles, namely to the effective diameter of spherical particles having the same volume as the aforementioned nanoparticles.

Furthermore, embodiments are possible where nanoparticles 254 are polydispersed, *i.e.* their effective diameters are characterized by a distribution N(D). Such distribution describes the number of nanoparticles per surface unit and unit interval of effective diameter in a neighborhood of the effective diameter D (that is, the number of particles per surface unit with diameter between D_1 and D_2 is equal to $N_{D1\text{-}D2}=\int_{D_1}^{D_1} N(D)dD$). Said effective diameters may be in the range [5 nm-350 nm], *i.e.* the distribution may be different from zero within that interval. In this case, considering that scattering efficiency grows approximately, *i.e.* in the limit of small particles, with the sixth power of the nanoparticle's diameter, the polydisperse distribution, with the aim of evaluating the minimum number per square meter of nanoparticles, behaves approximately as monodisperse with a representative diameter D'_{eff} defined by:

$$D'_{eff} = \left\{ \frac{1}{N} \int N(D) D^6 dD \right\}^{1/6}$$

where

$$N = \int N(D) dD$$

D'_{eff} may be selected to lie within any of the above intervals, *i.e.* within the range [5 nm-350 nm], preferably [10 nm-250 nm], more preferably [40 nm-180 nm], still more preferably [60 nm-150 nm].

However, alternatively, it is possible that the diffused-light generator 10 is constituted by or comprises a diffused-light source 260 in addition to the diffuser panel 250 as shown in Figs.

12A and 12B, or individually as shown in Fig. 12C. Differently from the diffuser panel 250, the diffused-light source 260 might emit diffused light independently from the direct-light source 12, since it comprises a second light-emitting device 266 which differs from the first light-emitting device of the direct-light source. This similarly relates to a sky imitating device that is configured as an additional diffused-light emitter.

As shown in Figs. 12A and 12B the diffused-light source 260 may be placed downstream or upstream relative to the diffuser panel 250. As described herein below, the diffused-light source 260 may be panel-shaped, shaped like a layer or be embodied as a layer stack. When combining any of the embodiments of Figs. 12A and 12B with the embodiment of Figs. 8 and 9, it should be noted that the low-angle white-light diffuser 230 may be positioned downstream or upstream both diffuser 250 and diffused-light source 260 or between them. Moreover, the functionality of the white-light diffuser 230 may be incorporated into the diffuser 250 and/or the diffused-light source 260. The diffused-light source 260 is capable of emitting light which is diffuse. Moreover, the diffused-light source is essentially transparent to the directed light 236 or an intermediate light evolving from the primary light and resulting in the directed light 236. As shown in Figs. 12A and 12B, the diffused-light source 260 can be positioned parallel to panel 250 and be virtually in contact with it. This similarly relates to a sky imitating device that is configured as an additional diffused-light emitter.

Similarly the following relates also to a sky imitating device that is configured as an additional diffused-light emitter.

The diffused-light source 260 can be realized using a diffuser panel 264 shaped as a light guide edge-lit by the second light-emitting device 266 shaped as, *e.g.* a linear stripe of LEDs or a fluorescent tube lamp, so that light emitted by second light-emitting device 266 propagates in guided-mode inside the diffuser panel 264, which diffuses it homogeneously. Such panel 264 can be, for example, a commercial diffuser suitable for side-lighting as, *e.g.*: “Acrylite® LED” or “Plexiglas® LED EndLighten”. Moreover, as shown in Fig. 13, the thickness along axis H of the diffuser panel 264 is negligible compared to thickness along direction K perpendicular to panel normal direction H.

In a particular configuration, the diffuser panel 264 is formed by a material, *e.g.*, polymethylmethacrylate, wherein microparticles of a material such as zinc oxide, are dispersed; such materials preferably do not absorb light with wavelengths in the visible range. In particular, the diameters of microparticles range from 2 μm to 20 μm.

When in use, part of the radiation guided by the diffuser panel 264 exits the diffuser panel 264 while propagating along the diffuser panel 264, *e.g.* due to diffusion by microparticles embedded into the diffuser panel 264. Since the diffuser panel 264 has negligible thickness along a direction H orthogonal to the panel major surfaces compared to edge-illumination direction K, the panel 264 is basically transparent to radiation propagating along direction H but works as diffuser for radiation propagating along direction K.

Moreover, assuming that the diffuser panel 264 is delimited on the upper and the lower side by a surface S_1, S_2, respectively, at least one out of such surfaces S_1, S_2 can be surface-finished to introduce roughness. Such roughness contributes in the diffusion by the diffuser panel 264 of the light generated by the second light-emitting device 266, the diffusion process being virtually homogeneous along any direction parallel to direction K. In a way known by itself, roughness can be designed so that great part of the light generated by the second light-emitting device 266 is scattered mainly through one between surfaces S_1, S_2, and in particular towards downstream direction 32. In the case in which at least one between surfaces S_1, S_2 features roughness, no microparticles may need to be dispersed in the diffuser panel 264. In any case, roughness may be present on both the surface S_1, S_2 of the diffuser panel 264.

In a different configuration, the diffused-light source 260 is not side-lit but comprises a second light-emitting device shaped as a substantially transparent and emitting layer obtained by means of an OLED film. Similarly to the side-lit panel source, the OLED film is also capable to generate diffused light with controlled color and intensity, being at the same time transparent to the light that crosses it along a direction perpendicular to its surface.

The diffused-light source 260 allows for changing the color and intensity of the diffused-light component 242, basically without changing the color and intensity of the transmitted component. For this aim, it is possible to act on the color and intensity of the light emitted by the second light-emitting device 266.

For example, aiming at reproducing the characteristics of late afternoon light, an incident light with low CCT, *e.g.* 2500 K, can be used; in this way, the color of the transmitted component 238 is similar to the color of sunlight before sunset when using a diffuser panel 250. Without the diffused-light source 260, the color of the component scattered by just the diffuser panel 250 would be remarkably different from the color of the corresponding natural component. As a matter of fact, what happens in nature is that the sky above the observer is lit by white sunlight, *i.e.* by sunlight that has not crossed the atmosphere yet, with CCT approximately equal to 6000 K, a much higher value than the lamp's CCT. As a consequence, the CCT of light scattered by the sky above the observer in the late afternoon hours is significantly higher than the CCT of light scattered by the diffuser panel 250, in the case in which the incident light has low CCT. However, if diffused-light source 260 is used, and particularly if the diffuser panel 250 is used together with the second light-emitting device 266, and this latter is made of an ensemble of red, green, blue LED emitters ("RGB"), it is possible to adjust the luminous flux of each of such three elements: this allows panel 264 to generate a scattered component with color and intensity such that the overall component that exits the diffused-light source 260 has the desired color. In other words, the diffused-light source 260 allows to uncouple the color of the transmitted component from the color of the scattered component. Moreover, if a lamp with adjustable CCT is used as source 260, the variation of natural lighting at different times of the day can be reproduced.

Panels 250 and 260 need not to be physically separated as depicted for ease of understanding. This applies also for the components drawn as being separated in other figures.

When the source 260 is used in the absence of the diffuser panel 250, the diffused-light generator 10 emits diffused light with higher CCT than the CCT of directed light 236 as long as source 260 is appropriately designed. Such diffused-light generator is, at least partially, light-transparent. In this context, the term "transparency" with reference to an optical element is used for indicating the so called "see through" property, *i.e.* the property of an optical element of transmitting image-forming light, *i.e.* of transmitting light rays which crosses the optical element without experiencing angular deviation or being deviated just by a small angle, *e.g.* by an angle smaller than 2.5°. In this context, therefore, the term "transmitted light" refers to the portion of the impinging light crossing the optical sample without experiencing relevant angular deviation, *e.g.* without experiencing angular deviation larger than

2.5°. Note that the present definition does not rely upon the concept of "regular transmittance", which in contrast accounts only for the light which is transmitted without any angular deviation.

More precisely, given a standard illuminant (*e.g.* a D65 source) which emits light uniformly from a circular emitting surface S_s, and given a standard observer O_s who sees the emitting surface S_s under a conical HWHM solid angle of 2.5°, preferably 1.5°, most preferably 0.5°, the diffused-light generator 10 is here defined as partially transparent if a luminance of the D65 emitting surface S_s as perceived by the standard observer O_s when the diffused-light generator 10 is interposed between the observer O_s and the surface S_s with its major surface oriented orthogonally to the line connecting the eye of the observer with the barycenter the surface S_s, is at least 50%, preferably at least 70%, more preferably at least 85% of a luminance perceived by the observer O_s when the diffused-light generator 10 is not interposed between the observer O_s and the surface S_s.

Summarizing, the diffused-light generator 10 may be embodied as a diffuser panel 250 and/or a diffused-light source 260, *i.e.* a light source that emits diffused light from a thin panel. It may be part of a sky (only) imitating device or a sun-sky imitating device.

In the case of using just the diffused-light source 260, the diffused-light source 260 does not operate for correcting the color of the diffused light as produced by the diffuser panel 250, but for generating the entire diffused component 242 – with or without adjustability of the diffused light CCT. Here, the advantage is that of having one, instead of two, diffusing elements, and therefore less losses. A first disadvantage may stem from the difficulty of obtaining sufficiently large luminance from source 260, due to the limit of side illumination in case of Fig. 13, for example. Moreover, the fact that the diffusing mechanism in the diffuser panel is identical to the mechanism taking place in the real sky might result in a luminance spatial and angular distribution of the diffuser 250 being more similar to the natural than compared with the source 260.

In accordance with many of the above described embodiments, the artificial illumination device further comprises an absorber made of light-absorbing material arranged so that the first emitting surface 28 shows a total reflectance factor $\eta_r < 0.4$. Preferably the absorber is broadband, i.e. not affecting the perceived color.

The absorber may be made of light-absorbing material. This light-absorbing material may, although not mentioned every time in the above description, have an absorption coefficient for visible light greater than 95 %, although 80% may also suffice. The light-absorbing material may be positioned downstream of the direct-light source's 12 first light-emitting device, where the term "downstream" is herein defined to follow the light propagation direction including light-bending at reflectors such as in the case of Figs. 6 and 7. On the other hand, the light-absorbing material is positioned upstream of the first emitting surface 28 as well as upstream the diffused-light generator 10 and the low-angle white-light diffuser 230 (if present) if they are positioned upstream of the first emitting surface 28. To be more precise, thus positioned, the light-absorbing material is configured to substantially absorb light rays which cross the direct-light source's first emitting surface 28 in an upstream direction and which in the absence of the absorber would not be directed toward the direct-light source's first light-emitting device.

In many of the above described embodiments, for example, the artificial illumination device comprises a light collimator being an optical element positioned downstream the first light-emitting device of the direct-light source and configured to reduce the divergence of the primary light generated by the first light-emitting device. In the above embodiments, the light collimator was embodied, for example, as a lens 48, 64, (such as dome lens, Fresnel lens, or microlens), a concavely curved mirror 152, a wedge-shaped lightguide 80 coupled to light exit layer 84, a light concentrator (112, 113, 140), but in general the light collimator may be any refractive, reflective (including total internal reflective), diffractive optical component or any system comprising a plurality of such optical components. In that case, the absorber has its light-absorbing material positioned such that the absorber substantially absorbs light rays which cross the direct-light sources first emitting surface 28 in the upstream/reverse direction and are redirected by the light collimator toward somewhere else than the first emitting device of the direct-light source, where the term "substantially" may mean that at least 70%, preferably 90%, or more preferably 95% of such light rays may be absorbed. In this circumstance, the absorber substantially contributes in reducing the amount of stray light in the directed light 236, *i.e.* the amount of light generated by the direct-light source 12 out of the narrow peak 30. In fact, it is noticed that such an embodiment guarantees for the direct-light source 12 a black appearance when off for observation directions departing from direction 32 of an angle larger than the angle width of the narrow peak 30. In other terms, the embodiment ensures that, under external illumination and when the direct-light source 12 is off, the first emitting surface 28 may re-emit light only from those directions under which the bright spot is seen when the direct-light source 12 is on. Moreover, such an embodiment ensures that light rays originated by the emitter which are scattered or reflected by the collimator or by other components of the device 20 positioned downstream the emitter and which in the absence of the absorber would not be ascribable to the collimated light beam exiting the first emitting surface 28 are absorbed.

The embodiments described in particular in connection with Figs. 2 to 9 concentrated on different exemplary implementations for the direct-light source 12 that can be used on a sun-sky imitating device as well as in a sun imitating device. These embodiments have in common that the direct-light source 12 comprises a first light-emitting device which is embodied in element 14, 46, 60, 114, 138, 150, respectively. This first light emitting device is configured to emit, *i.e.* actively generate, primary light 62. It might be an LED, an incandescent lamp, a fluorescent lamp, or a metal halide lamp or some other light source. Further, the direct-light source 12 comprises a first emitting surface 28 positioned downstream the light-emitting device. As far as the direct-light source's 12 ability to generate directed light 236 at the first emitting surface 28 is concerned, the diffused-light generator's 10 influence was left off by specifying the directed light 236 at the first emitting surface 28 in a state where the diffused-light generator 10 is removed. This corresponds to a sun imitating device.

The embodiments described in particular in connection with Figs. 8 and 9 concentrated on possible implementations for the diffused-light generator 10 and its relative position with respect to the direct-light source 12 and its individual components. The CCT of different light components occurring in the artificial illumination device was also considered.

Figs. 10B and 10C show two alternatives of positioning a diffused-light generator upstream relative to the first emitting surface 28 of the direct-light source 12. Fig. 10B illustrates the case of having a diffused-light generator 10 of the active type which is exemplarily almost completely transparent for the light impinging onto the input surface 33, *e.g.* for the primary light 62, so that the direct light would substantially directly contribute to the outer light 239 at the emitting surfaces 28 and 37, respectively. Nevertheless, however, it should be noted that a first angular light component differs from the direct light in that the first angular light component also comprises a contribution of the diffused light of the diffused-light generator 10. The latter contribution is, however, very small due to the small angular fragment covered by the narrow peak 30, and accordingly, all CCT relations relating the CCT of directed light 236 or CCT of transmitted light to the CTT of the diffused light mentioned above shall insofar also apply to the first light component.

Moreover, the first angular light component has a narrow angular support, being formed only by light rays propagating along directions within the narrow peak 30 (*i.e.* directions supporting the peak in the luminance profile). In contrast, the directed light 236 might feature the presence of background light at any angle.

Fig. 10C shows the case of the diffused-light generator 10 comprising a diffuser of wavelength selective diffusing efficiency as outlined above with, for example, a blur filter being placed between generator 10 and the outer emitting-surface formed by the emitting surface 28. In this case, merely the just mentioned transmitted variant of the direct light results at surfaces 28 and 37, respectively, and contributes to the outer light. Again, the angular light component of the outer light 239 within the narrow peak 30 differs from the just mentioned transmitted variant of the direct light in that the light component also comprises the respective angular fragment of the diffused light as generated by the diffused-light generator 10.

In connections with Figs. 14 to 20, general and specific embodiments of combined systems are described. The implementation of the respective sun-sky imitating devices and sky imitating devices are schematically illustrated. Implementations may be based on the exemplarily embodiments described in connection with Figs. 1 to 13 as well as known configurations described, e. g., in the initially mentioned background art. In general, directed-light components illustrated by a set of pointing arrows will be used to indicate the light component subject to sun imitation, while first diffused-light components illustrated by a set of arrows within a sphere for Lambertian-type emission will be used to indicate the light component subject to sky imitation.

Figs. 14A to 14C show generic illustrations of combined system with sky imitating device that is configured as an additional diffused-light emitter. Assuming an emission of blue diffused-light, the sky imitating device may be perceived as a window through which one looks into the sky only, e.g. in a northern direction when placed in the boreal hemisphere; thus, exemplarily the window may also be referred to as a “nordic” window. This window, through which no (imitated) sunlight shines, is provided in addition to the sun-sky imitating device. In consequence, the combined system features an overall emitting surface which is bigger than the surface portion emitting directed and diffused-light because the overall emitting surface comprises at least a portion (herein also referred to as the diffused-light emitting surface of the sky imitating device) emitting only a diffused-light component.

In the sectional view of Fig. 14A, a combined system 300 comprises a sun-sky imitating device 310 that generates two light components that are both emitted from the same area referred to as sun-sky imitating output area 312: a warm directional low CCT light component, which mimics the presence of the real sun and is referred to as a directed-light component 314, and a cold diffuse high CCT light component, which mimics the presence of the sky and is referred to as a first diffused-light component 316.

The directed-light component 314 is illustrated by a directed-light luminance angular profile 314A and the first diffused-light component 316 is illustrated by a diffused-light luminance angular profile 316A. Exemplarily, the first diffused-light component 316 may be generated by a Rayleigh-type scattering process from a portion of primary light generated by a primary light source; the remaining (unscattered) portion of the primary light forms the directed-light component 314 as described in the background art.

When looking at the sun-sky imitating output area 312, an observer 302 will perceive – due to the directionality of the directed light, i. e., the peak in the directed-light luminance angular profile 314A – a bright localized spot surrounded by a lit-up background originating from the diffused-light being received from all areas of the sun-sky imitating output area 312.

The combined system 300 further comprises a sky imitating device 320 that is configured as an additional diffused-light emitter. Accordingly, the sky imitating device 320 emits a second diffused-light component 326 from a sky imitating output area 322 for imitating the natural light from the sky only. The second diffused-light component 326 may have a spectrum that is close to or identical with the cold high CCT of the first diffused-light component 316 to similarly mimic the presence of the sky. In Fig. 14A, the second diffused-light component 326 is illustrated by a diffused-light luminance angular profile 326A. The second diffused-light component 326 is generated by a diffused-light generator that is separate to the primary light source of the sun-sky imitating device 310.

In general, the sun-sky imitating output area 312 and the sky imitating output area 322 extend in respective light output surfaces 312A, 322A, which are in this exemplary embodiment planes. In Fig. 14A, the light output surfaces 312A, 322A are parallel, even extend within a common plane. However, generally, the light output surfaces may be oriented with respect to each other by an inclination angle α that is equal to or smaller than 90° between the light output surfaces. Preferably, the inclination angle α is equal to or smaller than 45° and more preferably equal to or smaller than 25°. Moreover, referring to Fig. 14D, the output surfaces may have a curvature at least in one direction. Accordingly, output surfaces including the sun-sky imitating output area 312 and the sky imitating output area 322 of the sun-sky imitating device 310 and the sky imitating device 320, respectively, can be plane or curved surfaces.

It is noted that in the embodiment of Fig. 14A, the sun-sky imitating output area 312 and the sky imitating output area 322 are separated from each other such that there is some non-illuminating region between the same.

In the sectional view of Fig. 14B, a combined system 300A is illustrated that comprises a sky imitating device 330. Together with a sun imitating device 340, a first portion 330A of the sky imitating device 330 forms a sun-sky imitating device 310A, while a second portion 330B of the sky imitating device 330 forms a sky imitating device 320A. Obviously, in that arrangement, the sky imitating device 320A is at least in the region forming the sun-sky imitating output essentially transparent for the directed light component from the sun imitating device 340. Such a transparent feature of the sky imitating device 320A can further be used as explained in combination with further embodiments explained below.

In the embodiment of Fig. 14B, the respective sun-sky imitating output area and the respective sky imitating output area have direct transition into each other such that no space (i. e., non-illuminating region) is between the same. Generally, by coupled sun-sky imitating output areas and the respective sky imitating output areas, a continuity of the sky perception can be created. I.e., when looking at the combined system 300A from outside the directed light, a large sky imitating area can be seen, although the sun imitation can only be perceived in a specific region defined by the sun-sky imitating output area and the directionality of the directed-light component.

In some embodiments, the combined system is integrated in the wall or in the roof of a room within a building. When switched on, the combined systems mimics a window to the outside.

Fig. 14C illustrates a perspective schematic view onto a combined system 300B installed in a ceiling 304 of a room. An outer emitting surface 350 of the combined system 300B has a square shape. In a central region of the outer emitting surface 350, a sun-sky device 310B is provided with a sun-sky imitating output area 312B with a hexagonal shape. The sun-sky imitating output area 312B is delimited by a frame structure 352. Surrounding the frame structure 352 and thus the sun-sky imitating output area, a sky imitating output area 322B fills the area of the square shape of the outer emitting surface.

In the wording used before in connection with Figs. 1 to 13, the first and second emitting surfaces are associated with the internal part of the hexagon, while the diffused-light emitting surface of the sky imitating device is provided in the external part of the hexagon.

From the side, an observer may not see any directed light, while the diffused light is seen. The diffused light produced by the sun-sky imitating output area 312B (and thus associated with the second emitting surface of sun-sky imitating device) and the diffused light produced by the sky imitating output area 322B (and thus associated with the diffused-light emitting surface of the sun imitating device) may be very similar (even equal if similar technology is used as in Fig. 14B). This is the case even if the diffused-light emitting surface does not emit directed light.

Fig. 14D illustrates a further embodiment of a combined system 300'. The combined system 300' comprises a planar sun-sky imitating device 310 as described in connection with Fig. 14A, for example. The sun-sky imitating device 310 is accordingly associated with the planar light output surfaces 312A (as indicated by a dash-dotted line). For Fig. 14A, an installation of the sun-sky imitating device 310 at the ceiling of a room can be assumed; i.e., the sun-sky imitating device 310 extends horizontally above the observer 302. The combined system 300' comprises further a sky imitating device 320' that is curved, e.g., in one dimension. Thus, the sky imitating device 320' has a curved light output surfaces 322A' (as indicated by a dotted line). For example, the sky imitating device 320' may have the shape of a quarter of a pipe and run along a corner between ceiling and wall of the room.

Generally, a normal vector of a light output surface (including inter alia a plane or curved light output surface) is defined herein as an average vector of the normal vectors that are associated to the light output surface at each point of the same with an orientation along the light emission. Based thereon, a relative orientation between two light output surfaces can be defined as the angle between the normal vectors associated to the two light output surfaces, here of the sun-sky imitating device and the sky imitating device.

In Fig. 14D, a normal vector Nsun+sky of the planar light output surfaces 312A is indicated that extends vertically and points “down" to the floor.

Averaging the normal vectors that are associated with the light output surface 322A' of the sky imitating device 320' will result in a normal vector Nsky for the sky imitating device 320' that extends under an angle α of 45° with respect to the normal vector Nsun+sky as indicated in Fig. 14D.

While most exemplary embodiments disclosed herein for simplicity relate to planar and even parallel aligned light output surface, the skilled person will appreciate that various orientation of the normal vectors Nsun+sky and normal vector Nsky can be implemented based on, e.g., inclined or orthogonal planar light output surfaces or curved light output surface respectively oriented with respect to each other. One exemplary embodiment with α=90° relates to a planar sun-sky imitating device mounted at a ceiling of a room (as in Fig. 14D) and a planar sky imitating device mounted orthogonally at the wall of the room.

In other words, the combined system proposed herein emits a warm directional light component (with a narrow peak in the Luminous Intensity Distribution LID) and a cold diffused light component (with Lambertian like LID). The additionally provided / coupled sky device emits only cold diffused light component with chromatic and LID properties similar to those of the diffused light emitted by the sun-sky device. In this context, chromatic similarities are referred to the just noticeable difference as previously described. The LID similarity between two light emissions is experienced when the LIDs of the two emissions have substantially the same shape and/or have substantially the same full width half maximum FWHM.

In some embodiments, the diffused light components, generated from these two devices of the artificial illumination system / combined system, are coherent. In this context, coherent means that the diffused light components are chromatically similar and/or the chromatic differences between the two diffused light components are natural, in the sense that they are perceived as possible in nature. Moreover, coherent encompasses that the magnitude of the luminance emitted by the two devices is similar or again natural, in the sense that they are perceived as possible in nature.

In some embodiments, the sky imitating device emits a diffused-light component which has a luminance value similar to that of the diffused-light emitted by the sun-sky imitating device. In some embodiments similarity between two luminance values is achieved when the luminance value difference of one diffused light with respect to the other is less than 3 times, 2 times or even 1.5 times the higher luminance value between the two.

Generally, the sky imitating device / additional diffused-light emitter comprises an organic LED configuration (OLED-system), a display (e. g., an LCD display), or a backlight device, which comprise a plurality of light emitting device (e.g. LEDs) and a diffuser arranged downstream such devices.

In some embodiments, the additional diffused-light emitter is configured as a side-lit device, which comprises a diffuser and a plurality of light emitting devices that enters the diffuser from the edge.

In other embodiments, the sky imitating output area of the sky imitating device is larger than 1.2 times the sun-sky imitating output area (first/second emitting surface) of the sun imitating device. Extending the low-cost sky device in combination with a costly sun device ensures an enhancement of the space creative effect of the combination. Indeed, the infinite depth perception of the (imitated) sun that can be perceived by an observer looking at the first emitting surface and in particular the space creative effect deriving from such perception, is extended for continuity or proximity to the outer emitting surface including the whole outer emitting surface of the combined system.

It is worth to highlight that the combined system for artificial illumination disclosed herein produces the sun imitating directed-light component just from the sun-sky device, while the sky device does not contribute directed-light to the artificial illumination. Nonetheless, and surprisingly, the sky illumination device is perceived as an aperture from which the natural light enters, due to the synergic effect of the two types of devices.

The sectional view of Fig. 15 provides more details on an embodiment of a combined system 300C, in which a sun-sky imitating device 310C is made of a sky imitating device 330A and a sun imitating device 340A as schematically shown in Fig. 14B. The sun imitating device 340A is made of at least one structural unit 342 of a first light emitting device 344 and a related collimation optics 346 (also referred to as collimation optical element), see also the description in connecting with Fig. 2. Usually, there is a plurality of structural units 342 defining the sun imitating output area 348 in space, usually within a plane or curved surface in two dimensions.

The first light emitting device 344 can be made, for example, of a LED with a circular aperture, see also the description in connecting with Fig. 3. The dimension of the first light emitting device 344 is smaller than the associated collimation optical element 346. The collimating optic element is typically more than 2 times bigger than the first light emitting device (usually measured as projection with respect to the sun imitating output area 348).

Generally, the collimating optics 346 can have refractive or reflective properties or both. As mentioned in the background art and above, light absorbing material may be placed between the first light emitting device 344 and the related collimation optics 346.

The sky imitating device 330 is typically placed downstream the sun imitating device 340 and is implemented, for example, as an active light emitting layer such as a side lit diffusing panel as described in connection with Fig. 13 or an OLED-based system.

Passive scattering layer may show color separation properties. For example, in a passive scattering layer, the sky imitating device is not directly emitting but primary light of the sun imitating directed light (generated, for example, by the sun imitating device) interacts with the sky imitating device and some of its spectral components are scattered (diffused) with more probability than others such as in the known Rayleigh-type diffuser panels, see also the description in connecting with Fig. 11.

As in Fig. 14B, the size of the sky imitating device 330, specifically a region 332 from which diffused light is emitted, is larger than the sun imitating device 340, specifically the sun imitating output area 348. The portion of the region that is not downstream (or in some embodiments upstream) of the sun imitating output area 348, forms then a sky (only) imitating output area associated to a sky imitating device 320C.

The embodiments illustrated in Figs. 14B and 15 can extend over a large area and may be limited in thickness depending on the first light emitting device 344 and the related collimation optics 346.

In addition, there are also projector-based combined system using sun-sky imitating setups as the ones described in the mentioned background art WO 2017/084756 A1. Projector-based combined systems 300D and 300E are schematically illustrated in Figs. 16A and 16B, respectively.

As can be seen, the configuration of the combined systems 300D and 300E with respect to the generating of the directed-light component 314 are similar in Figs. 16A and 16B. Different is the generation of the first and second diffused-light components 316 and 322.

Specifically, primary light being the basis for the sun imitating directed-light is generated with a directed light source 360 (the projector illustrated by LEDs 362 and collimation optics 364 in Figs. 16A and 16B). The primary light is then guided (redirected and/or collimated by optical beam guiding elements 366) to path through a directed-light output area 368.

The directed light source 360 and the optical beam guiding elements 366 are mounted within a housing 370. The housing 370 may have specifically absorbing inner side walls to reduce any back reflection of light entering the housing 370 through the directed-light output area 368.

In Fig. 16A, a Rayleigh panel 372 as known in the background art and described herein is position across the directed-light output area 368 for passively generating the first diffused-light component 316. The second diffused light 322 component is generated, e.g., by an OLED-array 374 comprising a plurality of blue emitting OLEDs.

In Fig. 16B, a side-lit scattering panel 376 as known in the background art and described herein is position across the directed-light output area and extends further along the housing, thereby providing a large sky imitating output area. The side-lit scattering panel 376 may comprise blue emitting LEDs coupling light from the sides into a diffuser panel providing uniformly diffused light by scattering through the faces of the diffuser panel.

The side-lit panel 376 is transparent for the directed-light such that in the area of the directed-light output area, the direct light passed through.

It is noted that the embodiments in Figs 14B, 15, 16, 17, and 19, for example, illustrate that a common component can be used in both devices to generate diffused light. Specifically, the sky imitating device is respectively configured as a diffused light generator that is partly used as a component of the sun-sky imitating device to emit the first diffused-light component from the directed-light output area 368 associated, e.g., with the directed light source 360, and partly used to emit the second diffused-light component from the diffused-light output area. These types of configuration can in particular be implemented, when an active diffused light source is used such as a side-lit panel. Moreover, these types of implementation can be implemented if it is intended to provide a continuous area for emitting diffused light, i.e., to provide sky imitating output area and the sun-sky imitating output area directly next to each other.

It will be understood that the combined systems 300D and 300E shown in Figs. 16A and 16B are embodiments relating to Fig. 14A (distance between sun-sky imitating output area and sky-imitating output area) and Fig. 14B (continuous transition).

In some embodiments, the direction and the Full Width at Half Maximum of the LID of the warm directional light component from the projector can be modified through a collimation and folding optics. In some embodiments, instead of a reflective component (indicated in Figs. 16A and 16B) a refractive component can be implemented to change the direction of the narrow peak of the LID or to change the FWHM of the LID or both.

As illustrated in Figs. 16A and 6B, the additional diffused-light emitter effectively extends the area that is perceived as an aperture, by recovering the usage of area that would have been necessary even if only the sun-sky illuminating device had been present (specifically to low wall of the housing that is larger than the directed-light output area). Thus, the additional diffused light emitter is positioned in the footprint of the sun-sky imitating device. In consequence, the area used by the combined system is the same as the one used by just the sun-sky imitating device. However, the combination of the additional diffused light emitter with the sun-sky imitating device allows for the creation of a larger perceptive scenario.

The sectional views of Fig. 17A and 17B illustrate embodiments of combined systems300F, 300G in which a directed-light source 370 is used to generate sun imitating directed-light 372 as in Figs. 16A and 16B. However, the directed-light source 370 is not encompassed by a housing, instead it is installed within, e. g., a room 306 and the primary light 372 is directed onto a diffused-light generator 374 forming the sky imitating device.

In the sectional view shown in Fig. 17A, the diffused-light generator 374 has a panel shape and is mounted at the ceiling (or alternatively a wall) of a room. The diffused-light generator 374 defines a region 332A from which diffused light is emitted. At least a portion of the diffused-light generator 374 has a reflective layer 376 at the back side facing the ceiling/wall.

The sun imitating directed-light 372 is directed onto the reflective layer 376 and is reflected back into the room 306. As the reflective layer 376 extends planar (as the diffused-light generator 374 is a panel), the divergence of the sun imitating directed-light 372 is not modified by the reflection.

The observer 302 will perceive (imitated) sunlight (directed-light component 314) emitted from the region of the reflective layer 376 as well as (imitated) skylight (first diffused-light component 316). In addition, diffused light (second diffused-light component 326) will be perceived from the remaining portion of the diffused-light generator 374.

In the wording used in connection with Figs. 1 to 13, the direct light that exits the first emitting surface (originating from the sun device in the drawings) goes through the diffused-light source (i.e. the sky device in the picture) and is reflected by a mirror (the reflective layer 376). In such embodiments, the presence of the mirror may enhance the efficiency in the diffused light emission, indeed some diffused light sources, such as a side lit diffusers or OLED-based systems, emit light isotropically and a portion of the light emitted is shined in the direction of the mirror. In absence of the mirror such portion of light could be significantly absorbed before reaching the illuminated ambient. Thus, in some embodiments, as shown in Fig 17A, the reflective layer 376 extends over the complete output area of the combined system.

The displacement of the sun device with respect to the sky device may even reduce the space occupation of the artificial illumination device. Indeed, in some embodiments, the combined system may be installed in an airplane and, depending on the position where the sky appearance have to be recreated, constrains on the thickness of the device could be imposed. In such scenarios, it may be useful to spare space occupancy in specific positions.

A modified diffused-light generator 374A is used in the combined system 300G shown in the perspective view of Fig. 17B. Specifically, the diffused-light generator 374A (a portion of it forming the sky imitating device and another portion the additional sky imitating device) and/or the mirror (i. e., a reflective layer 376A) are curved in at least one direction.

The curved configuration may serve the need to follow the shape of the environment of implementation, e.g. the aircraft fuselage shape. Moreover, it may serve optical aspects. For example, the curved mirror may be used as a collimating and folding optics to achieve the required narrow peak of the first light component downstream the reflective layer 376A (potentially in a desired directionality). The collimation is indicated schematically in Fig. 17B.

Referring to the schematic view shown in Fig. 18A, a combined system 300H for artificial illumination can be integrated in a vehicle, e. g., in a roof of a car or in a different vehicle for transportation such as trains or airplanes. As exemplary components, the sun-sky imitating device 310 and the additional sky imitating device 320 of Fig. 14A are illustrated at the ceiling of a car 380. The combined system 300His configured as a part of the main casing.

In such embodiments, the light exits the combined system 300H and illuminates the internal environment of the car 380, while the opposite surface of the combined system 300H is exposed to the external environment. The external surface may thus be exposed to natural sunlight.

The embodiment of a combined system 300I shown schematically in Fig. 18B relates to the use of a sky imitating device 320 in such an installation situation. Specifically, the sky imitating device 320 is configured to be light transparent (this means that the device is at least partially see-through).

This applies in particular to automotive applications, in particular for vehicles that have a transparent roof (e.g., glass roof) allowing for seeing the external scenario. The described feature, also referred to as “panorama” or “panorama view”, is interesting because an occupant in the vehicle can see the world outside. Notably, the transparent material of the sky imitating device 320 should allow seeing the objects outside and not just light entering such as through a frosted (white satin) glass.

When the sun-sky imitating 310 device is switched on and emits light, the sky imitating device is also switched on and emits e.g. blue light.

In the combined system 300I, a shutter 382 is further provided on top of the light transmitting sky imitating device 320. Thereby, image forming light coming from the exterior may be absorbed by the shutter 382, e.g. a closed light shutter layer. Such light shutter layer may be set open and be light transmitting when the sun-sky imitating device 310 and the sky imitating device 320 are turned off. In this OFF state, the sun-sky imitating device 310 appears black, while the environment over the sky imitating device 320 can be seen by a person sitting in the car 380. Thus, the panorama view is preserved while, at the same time, an artificial illumination device is integrated in the same roof.

In some embodiments, the panorama and the illumination devices 310, 320 cooperate to lit the interior.

In some embodiments, the light shutter layer comprises a light absorbing material that, in an open state, is mechanically moved away from the transparent portion of the sky imitating device 320. In a closed state, the light absorbing material is positioned to cover the transparent portion of the sky imitating device 320.

In some embodiments, the light shutter layer can be made of a tunable smart material in which light transmitting properties can be electronically tuned. Between such materials electrochromic, electro wettable or Polymer Dispersed Liquid Crystals (PDLC) are implementing options. For example, micro-PDLC may be implemented alone or in combination with other smart-materials, such as electrochromic and electro-wettable devices.

Optical behavior of electrochromic device can be controlled with continuity. In particular light transmission, absorption, and/or reflectance can be tuned in reversible manner, applying an external voltage. The basic principles on which such devices works is the variation of optical performances of some materials by changing their oxidation state. Such devices are substantially electrochromic cells. The electrochromic devices could act as a black background layers that can be switched in a transparent state.

Polymer-dispersed liquid-crystal devices are, for example, made of micro-sized domains of liquid crystals dispersed into a polymer matrix. Such material made of polymer and liquid crystals can be placed between two substrates of glass or plastic whose internal side is covered by a thin, transparent, and conductive layer. This ensemble, in the end, will act as a capacitor. Applying voltage to the electrodes will align liquid crystal, located in the micro-sized domains, reducing the refractive index mismatch between such domains and the matrix. This will reduce the scattering properties of the domains. Thereby, the material will change from a “milky white” appearance to a “transparent state”. This feature can be used to implement a switchable see-though properties into the sky imitating device.

The electrowetting mechanism is a tool in microfluidics that enables control over fluid shape and flow by electrical signals. It allows controls of individual droplets and independently manipulating them over a planar electrode array. An electro-wetting device with tunable transmissive properties can be used to implement a light shutter layer in the sky imitating device. Specifically, in some configuration of electro-wetting cells, a light absorbing oil may be displaced along the complete unit, making that pixel completely light absorbing. Applying voltage to the electrodes of the cell, the oil could be confined, due to an electro-wetting process, in a small portion of the pixel, leaving it substantially transmissive. In a combined system, each electro-wetting cell of the electro-wetting device can behave as a tunable optical aperture (or diaphragm). Thereby, the device can switch from a state substantially light absorbing, to a state substantially transmissive. Furthermore, this behavior can be spatially controlled when, in some configuration, a plurality of electro-wetting cell can be independently activated.

In some embodiments, especially for architectural applications, a static (not tunable) light absorbing layer is positioned upstream the sky imitating device. In such embodiments, it is possible to reduce the cost of an artificial window sacrificing the view of the sun disk from some observing positions not easily accessible.

In other embodiments, sun-sky imitating devices are coupled to transparent windows. A light shutter layer allows the control of the fraction of light transmission through the light transparent window.

As indicated above, in some installations of combined systems, an external surface may be exposed to the sunlight. In that case, as schematically shown in the combined system 300J of Fig. 10, a photovoltaic system 390 can be provided at the backside of any one of the components and be used to produce electric energy from the sunlight. In some embodiments, the photovoltaic system 390 may be positioned on the sun-sky device and/or on the additional light emitter. Generally, photovoltaics systems are devices which allow the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect (e. g., solar panels that generate electrical power).

In some embodiments, a battery may be provide locally to store the energy collected by the photovoltaic system 390 and to power the combined system 300J. For example, such combination can be used to harvest energy during the day and light the interior with the artificial light at night.

Fig. 20 illustrates the concept that an additional diffused-light emitter (sky imitating device 320) can produce a diffused light which is tuned in terms of luminance and chromaticity. The underlying intention may be to present described variations in order to improve the perception of naturalness of the artificial illumination system.

In some embodiments, the chromaticity of the diffused light produced by the additional diffused-light emitter is similar to the diffused light produced by the sun-sky imitating device 310. In other embodiments, the chromaticity values and/or the luminance of the diffused light vary according to the relative distance between the point of the emission on the diffused light emitting area and a reference point B (for example, a barycenter of the second emitting surface / the sun-sky imitating output area 312).

In Fig. 20, the distance is represented for three different points (associated with areas A1, A2, A3 within the sky imitating output area 322) with reference to the reference point B (exemplarily the barycenter of the second emitting surface). The luminance of the points are labeled as LA1, LA2, LA3, and vary as a function of the distance d1, d2, d3. For example, the luminance decreases with increasing distance, compared to the luminance L310 of the sun-sky imitating device 310.

Also the chromaticity coordinates of the diffused light may vary accordingly or independently to the luminance or the distance, or generally may show a dependence in function of the barycenter of the sun-sky device, e. g., the distance.

For completeness, Fig. 20 also illustrates dimensional aspects such as, for the sun-sky imitating output area 312, a transversal dimension D310 (e. g. of at least 7 cm or at least 10 cm or at least 15 cm), wherein the transversal dimension is the longest line segment LS joining two points of a perimeter Psun+sky of the sun-sky imitating output area 312. Similarly, the sky imitating output area 322 has a transversal dimension D320 that is the longest line segment LS joining two points of a perimeter Psky of the sky imitating output area 322. Furthermore, a distance D between the sun-sky imitating device 310 and the sky imitating device 320 is indicated. The distance D is smaller than a predefined value that is given by the maximum of the transversal dimension D310 of the sun-sky imitating device 310 and the transversal dimension D320 of the sky imitating device D320.

In some embodiments, the sun-sky imitating device is an artificial illumination device for generating natural light similar to that from the sun and the sky with making an observer experience a visual infinite-depth perception of a sky and sun image when the observer directly looks at the artificial illumination device.

In some embodiments, a direct-light source (12) that comprises

a first light-emitting device (14) configured to emit a primary light (62), and

a first emitting surface (28) positioned downstream of the first light-emitting device; and

wherein the direct-light source (12) is configured so that the direct-light source (12) produces from the primary light (62) a direct light (236) that exits the first emitting surface (28) with a luminance profile $L_{direct}(x, y, \vartheta, \varphi)$

which is - with respect to the spatial coordinates (x, y) - uniform across the first emitting surface (28) such that the ratio between a standard deviation of the luminance spatial fluctuations and a luminance average value does not exceed the value of 0.3 within any 10 mm diameter spatial circular areas and for at least 90% of the first emitting surface, for any fixed azimuthal angle φ and for any fixed polar angle ϑ greater than $3\vartheta_{HWHM}$ and

which has a peak (30) in the angular distribution around a direct-light direction (32), such that the luminance profile drops below 1% of a maximum value of the luminance profile for polar angles $\vartheta > 3\vartheta_{HWHM}$,

where ϑ_{HWHM} is the HWHM of a mean polar-angle distribution being an average of the luminance profile over all the first emitting surface (28) and all azimuthal directions and $\vartheta_{HWHM} \leq 5°$, and

wherein the luminance profile for polar angles $\vartheta \leq \vartheta_{HWHM}$ is virtually independent on the azimuthal angle φ, wherein the polar angles and the azimuthal angles are measured in an angular coordinate system assigning $\vartheta = 0$ to the direct light direction corresponding to an average of the directions of the maximum value of the luminance profile, averaged over all the first emitting surface (28).

In some embodiments, a diffused-light generator (10) as it can be used in the sun-sky imitating device or in the sky imitating device:

is at least partially light-transparent,

is positioned downstream of the first light-emitting device,

comprises a second emitting surface (34), and

is configured to emit from the second emitting surface (34) diffused light with a spatial uniformity and a smooth angular dependence.

In some embodiments, one of the first emitting surface (28) and the second emitting surface (34) is positioned downstream with respect to the other and forms an outer emitting surface of the sun-sky imitating device or both the first emitting surface (28) and the second emitting surface (34) coincide to form the outer emitting surface (37) of the sun-sky imitating device.

In some embodiments, the sun-sky imitating device is configured such that the direct-light source (12) and the diffused-light generator (10) co-operate to form outer light at the outer emitting surface (37) which comprises a first (directed-) light component which propagates along directions contained within the peak (30) and a second (diffused-) light component which propagates along directions spaced apart from the peak (30), andthe first light component has a correlated color temperature, CCT, which is at least 1.2 times lower than a CCT of the second light component.

In some embodiments, regarding a direct-light uniformity close to direction (32), the luminance profile

- does not have spatial fluctuations in a (local) polar angle leading to (local) maximum luminance with standard deviation larger than 20% of $\vartheta_{\mathrm{HWHM}}$ within spatial areas of 5 cm diameter, preferably 10 cm diameter, more preferably 20 cm diameter, and
- does not exhibit spatial fluctuations in the (local) polar angle leading to (local) maximum luminance with standard deviation larger than $\vartheta_{\mathrm{HWHM}}$ within the entire at least 90% of the entire light-emitting surface, and

wherein in particular $\vartheta_{\mathrm{HWHM}} \leq 2.5°$.

In some embodiments, the weakly dependence of the luminance profile from the azimuthal coordinate φ is such that, for each position (x,y), the ϑ,φ region, outside which L_{direct} drops below 10% of the maximum, is substantially a cone with circular base and/or it is such that the difference between max and min polar angles of said region normalized to the half sum of the same quantities is below 0.5, preferably below 0.2, most preferably below 0.1 for any position in the sample.

In some embodiments, the direct-light source (12) is configured such that the ratio between a standard deviation of the luminance spatial fluctuations and a luminance average value does not exceed the value of 0.4 within the entire at least 90% of the first emitting surface, for any fixed azimuthal angle φ and for any fixed polar angle ϑ greater than $3\vartheta_{\mathrm{HWHM}}$.

Although the preferred embodiments of this invention have been described herein, improvements and modifications may be incorporated without departing from the scope of the following claims.

Claims

1. A combined system (300) comprising:

a sun-sky imitating device (310) that is configured as an artificial illumination device (20) for generating light with a luminance profile and an appearance, which feature a directed-light component (314) and a first diffused-light component (316) that are emitted from a sun-sky imitating output area (312) for imitating the natural light from the sun and the sky, respectively, and the sun-sky imitating output area (312) has a transversal dimension (D310) of at least 7 cm, wherein the transversal dimension is the longest line segment (LS) joining two points of a perimeter (Psun+sky) of the sun-sky imitating output area (312); and

a sky imitating device (320) that is configured as an additional diffused-light emitter to emit a second diffused-light component (326) from a sky imitating output area (322) for imitating the natural light from the sky only and the sky imitating output area (322) has a transversal dimension (D320) that is the longest line segment joining two points of a perimeter (Psky) of the sky imitating output area (322), wherein

the sun-sky imitating device (310) and the sky imitating device (320) are placed one with respect to the other at a distance (D) smaller than a predefined value that is given by 10 times the maximum of the transversal dimension (D310) of the sun-sky imitating device (310) and the transversal dimension (D320) of the sky imitating device (320).

2. The combined system (300) of claim 1 or 25, wherein the predefined value is given by 5 times, preferably 3 times the maximum of the transversal dimension (D310) of the sun-sky imitating device (310) and the transversal dimension (D320) of the sky imitating device (320).

3. The combined system (300) of claim 1 or 2 or 25, wherein the transversal dimension (D310) of the sun-sky imitating device (310) is at least 10 cm such as at least 15 cm; and/or

the sun-sky imitating device (310) and the sky imitating device (320) are carried by a common support structure and/or share a common housing (370).

4. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sun-sky imitating output area (312) and the sky imitating output area (322) extend in respective light output surfaces, in particular planes, with an inclination angle (α) equal to or smaller than 90°, or equal to or smaller than 45°, or equal to or smaller than 25° between the light output surfaces, and

wherein the inclination angle between the light output surfaces is smaller than 20° or 15° or the light output surfaces form substantially parallel planes or the light output surfaces extend each other.

5. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sun-sky imitating device (310) comprises a collimation and/or folding optics (366), and a direction and a full width at half maximum of a luminance intensity distribution of the directed-light component (314) is formed by the collimation and/or folding optics (366).

6. The combined system (300) of any one of the preceding claims or of claim 25, wherein the first diffused-light component (316) and the second diffused-light component (326) are chromatically similar, wherein two colors are considered similar if their color difference is equal to or smaller than 4 times, preferably equal to or smaller than 3 times, even more preferably equal to or smaller than 2 times a just noticeable difference defined in CIE76 color space, or have a chromatic difference limited by natural chromatic appearances, and/or

wherein the first diffused-light component (316) and the second diffused-light component (326) have luminance values that differ by a luminance value difference of the first diffused-light component (316) with respect to the second-diffused light component (326) that is less than 3 times, 2 times or even 1.5 times the larger luminance value of the first diffused-light component (316) and the second-diffused light component (326).

7. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sun-sky imitating output area (312) is substantially surrounded by the sky imitating output area (322), and/or

wherein the emitting side of the combined system (300) comprises an inner region such as a hexagonally shaped region and an outer region surrounding the inner region, and the sun-sky imitating output area (312) is provided in the inner region, and the sky imitating output area (322) is provided in the outer region.

8. The combined system (300) of any one of the preceding claims or of claim 25,

wherein the sky imitating device (320) is configured as an additional diffused-light source that is provided additionally to a diffused light source of the sun-sky imitating device (310), or

wherein the sky imitating device (320) is configured as a diffused light source that is partly used as a component of the sun-sky imitating device (310) to emit the first diffused-light component (316) from the directed-light output area (368) associated with a directed light source (360), and partly used to emit the second diffused-light component (326) from the diffused-light output area (322), and/or

wherein the sky imitating output area (322) is larger than 1.2 times the sun-sky imitating output area (312).

9. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sky imitating device (320) is configured as the additional diffused-light emitter by being configured as one of

a display such as an OLED display or an LCD display,

a backlight device, which comprises a plurality of light emitting devices (14), such as LEDs, and a diffuser (250) downstream of the light emitting devices (14), and

a side-lit device, which comprises a diffuser panel (264) and a plurality of light emitting devices (266) that emit into the diffuser panel (264) from an edge of the diffuser panel (264).

10. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sun-sky imitating device (310) comprises

a direct-light source (12) comprising a plurality of first light emitting devices (14), such as LEDs (44), with in particular a circular aperture, configured to produce directional light as a basis for the directed-light component (314) for imitating the natural light from the sun, and

a diffused-light source (10) configured to emit the diffused-light component for imitating the natural light from the sky, and wherein the sun-sky imitating output area (312) is a common output area that is defined in a light output surface of the sun-sky imitating device (310) and emits the directed-light component (314) and the first diffused-light component (316); and

wherein optionally the sun-sky imitating device (310) further comprises collimation optics (48) with refractive and/or reflective properties and, when the direct-light source (12) comprises a plurality of LEDs (44), respective collimation optical elements of the collimation optics (48) are associated to the LEDs of the plurality of the LEDs (44) and are in particular more than 2 times bigger than an LED of the plurality of the LEDs (44), and

wherein optionally the sun-sky imitating device (310) further comprises light absorbing material placed between the first light emitting device (14) and the related collimation optics (48).

11. The combined system (300) of claim 10, wherein

the direct-light source (12) is configured to emit a primary light (62), and is associated with a first emitting surface (28) positioned downstream the first light-emitting device (14),

the diffused-light source (10) is at least partially light-transparent and positioned downstream of the first light-emitting device (14), wherein the diffused-light source (10) is associated with a second emitting surface (34) and is configured to cause the first diffused-light component (316) at the second emitting surface (34), and

wherein the sky imitating device (320), which is configured as the additional diffused-light emitter, is positioned such that the sky imitating output area (322) is laterally shifted with respect to the sun-sky imitating device (310) so that the primary light (62) does not impinge on the additional diffused-light emitter, and

the additional diffused-light emitter comprises a diffused-light emitting surface, which is associated with the diffused-light output area, and is configured to emit the second diffused-light component (326) at the diffused-light emitting surface,

wherein the direct-light source (12) is configured so that, with the diffused-light source (10) being removed if positioned upstream of the first emitting surface (28), the direct-light source (12) produces from the primary light (62) the directed-light component (236) that exits the first emitting surface (28) with a luminance profile which has a peak (30) in the angular distribution around a direct-light direction (32),

wherein one of the first emitting surface (28) and the second emitting surface (34) is positioned downstream with respect to the other and forms the sun-sky imitating output area (312) of the sun-sky imitating device (310) or both the first emitting surface (28) and the second emitting surface (34) coincide to form the sun-sky imitating output area (312) of the sun-sky imitating device (310),

wherein the sun-sky imitating device (310) is configured such that the direct-light source (12) and the diffused-light source (10) co-operate to form at the sun-sky imitating output area (312) the directed-light component (314), which propagates along directions contained within the peak (30), and

the first diffused-light component (316) which propagates along directions spaced apart from the peak (30), has a correlated color temperature, and the directed-light component (314) has a correlated color temperature that is lower than a correlated color temperature of the first diffused-light component (316), and the second diffused-light component (326) has a correlated color temperature optionally corresponding to the correlated color temperature of the first diffused-light component (316).

12. The combined system (300) of claim 10 or claim 11, wherein the chromaticity values and/or the luminance of the first diffused-light component (316) and the second diffused-light component (326) varies according to a relative distance between a point of the emission on the sky imitating output area (322) and a reference point, such as optionally the barycenter, of the sun-sky imitating output area (312) associated with the first diffused light component (316).

13. The combined system (300) of anyone of claims 10 to 12, wherein the common output area of the sun-sky imitating device (310) is part of an outer emitting surface of the combined system, the outer emitting surface being the minimum area from which the light produced by the combined system emerges and propagates into the ambience,

wherein the direct-light source is configured to produce the directed-light component at the outer emitting surface with a luminance profile, which has a peak in the angular distribution around a directed-light direction (32), wherein the directed-light component (314) exits from at least 10% and less than 90% of the area of the outer emitting surface, wherein the combined system (300) is configured such that the direct-light source (12) and the diffused light source (10) and the at least one sky imitating device (320) co-operate to form an outer light, which exits from the outer emitting surface.

14. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sun-sky imitating device (310) is structurally coupled to the sky imitating device (320), in particular for forming a continuity of a sky perception.

15. The combined system (300) of any one of the preceding claims or of claim 25, further comprising a photovoltaic system (390) mounted at an external surface of the combined system (300), which is exposed to an outdoor, and in particular wherein the photovoltaic system (390) is positioned on the sun-sky imitating device (310) and/or on the sky imitating device (320).

16. The combined system (300) of any one of the preceding claims or of claim 25, integrated in a vehicle, such as in a roof of a car (380) or in a transportation unit such as a train or plain, wherein the combined systems (300) is a part of a main casing of the vehicle, and wherein in particular the emitted light exits the combined system (300) to light an internal environment of the vehicle, and an external surface of the combined system (300) is exposed to an external environment, wherein the external surface is in particular exposed to external light such as the sunlight, and a photovoltaic system (390) is provided at the external surface to produce electric energy from the external light.

17. The combined system (300) of claim 15 or 16, further comprising a battery used to store the energy collected by the photovoltaic system (390) and to power the combined system (300).

18. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sky imitating device (320) and/or a folding mirror (366) of the sun-sky imitating device (310) comprise an output surface that is curved in at least one direction.

19. The combined system (300) of any one of the preceding claims or of claim 25, wherein the sun-sky imitating device (310) comprises a housing (370) that defines a footprint of the sun-sky imitating device (310), and the sky imitating device (320) is positioned to recover the usage of an area associated with the footprint.

20. A sky imitating device (320) for use in a combined system (300) as recited in any of the preceding claims, wherein the sky imitating device further comprises a

light shutter layer with a light shutter (382), that is in particular positioned upstream of a diffuser of the sky imitating device (320).

21. The sky imitating device (320) of claim 20, installed in a combined system (300) as recited in any one of claims 1 to 19 or in claim 25 such that, for an operation state, in which the sun-sky imitating device (310) and the sky imitating device (320) emit, any image forming light coming from an exterior is absorbed by the light shutter (382) being in a closed state, and for an operation state, in which the sun-sky imitating device (310) and sky imitating device (320) are turned off, the light shutter (392) is in an open state and transmits light from the exterior.

22. The sky imitating device (320) of claim 20 or claim 21, installed in a combined system (300) next to a transparent window, wherein the light shutter (382) comprises a layer of a light absorbing material that is configured such that, in an open state of the light shutter (382), the light absorbing material layer is mechanically moved away from the transparent window, and in a closed state of the light shutter (382), the light absorbing material layer is positioned to cover the transparent window.

23. The sky imitating device of an one of claims 20 to 22, wherein the light shutter layer is made of a tunable smart material, in which light transmitting properties are electronically tunable, such as electrochromic, electro-wettable or Polymer Dispersed Liquid Crystals (PDLC) materials.

24. A control method for operating a combined system (300) of any one of claims 1 to 19 or of claim 25, wherein

a color of a diffused light portion of the second diffused light component (326) emitted by the sky imitating device (320) is controlled based on a distance (d) from the sun-sky imitating device (310) to a point of emission of the diffused light portion.

25. A combined system (300) comprising:

a directed light source (360) that is configured as an artificial illumination device (20) for generating light with a luminance profile and an appearance, which feature a directed-light component (314) that is emitted from a directed-light output area (368) for imitating the natural light from the sun and the directed-light output area (368) has a transversal dimension (D310) of at least 7 cm, wherein the transversal dimension as the longest line segment joining two points of a perimeter of the sun-sky imitating output area (312); and

a sky imitating device (320) that is configured as a diffused-light emitter to emit diffused light including a first diffused-light component (316) and a second diffused-light component (326), wherein the first diffused-light component (316) is emitted from the directed-light output area (368) for adding the imitation of natural light from the sky to the imitation of the natural light of the sun, and the second diffused-light component (326) is emitted from a sky imitating output area (322) for imitating the natural light from the sky only.

26. The combined system (300) of claim 25, wherein the diffused light is emitted from a surface area of the combined system that is larger than the directed-light output area (368), and/or

wherein the combined system (300) is further configured as in any one of claims 1 to 19.

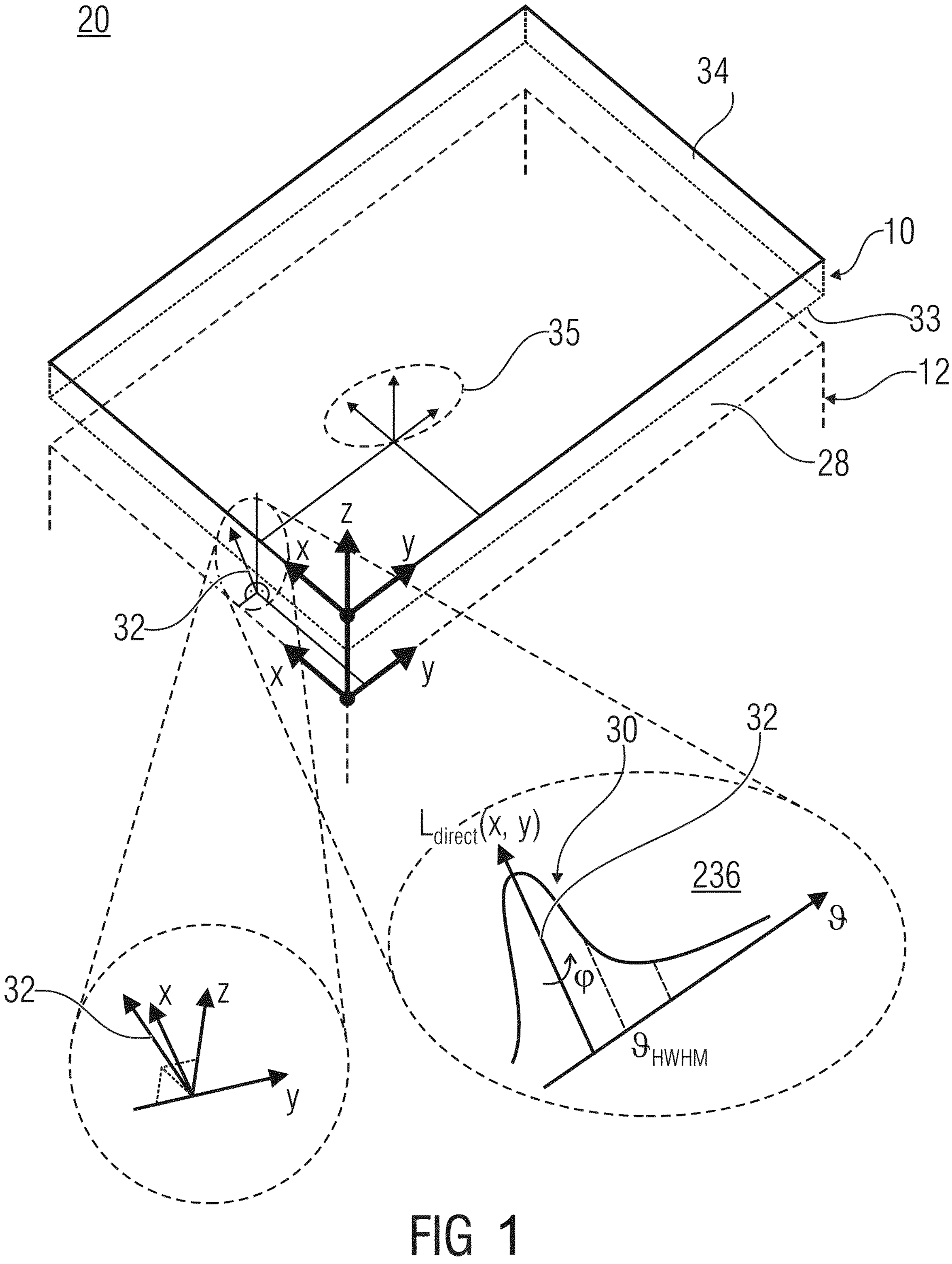


FIG 1

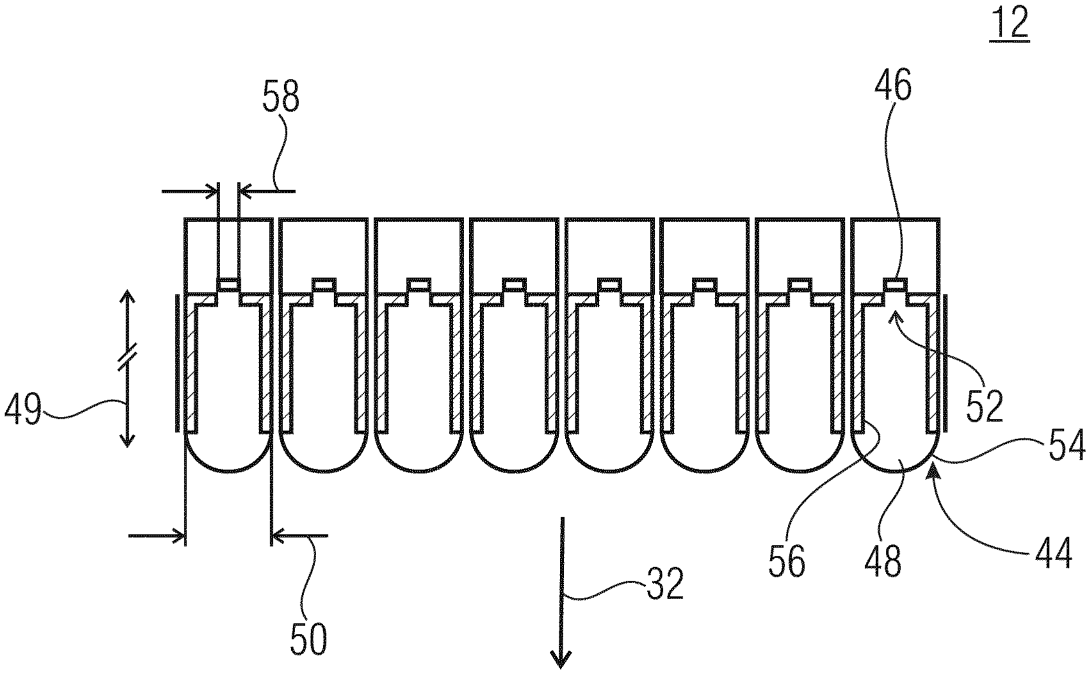


FIG 2

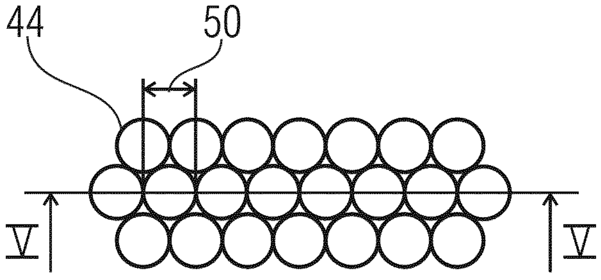


FIG 3

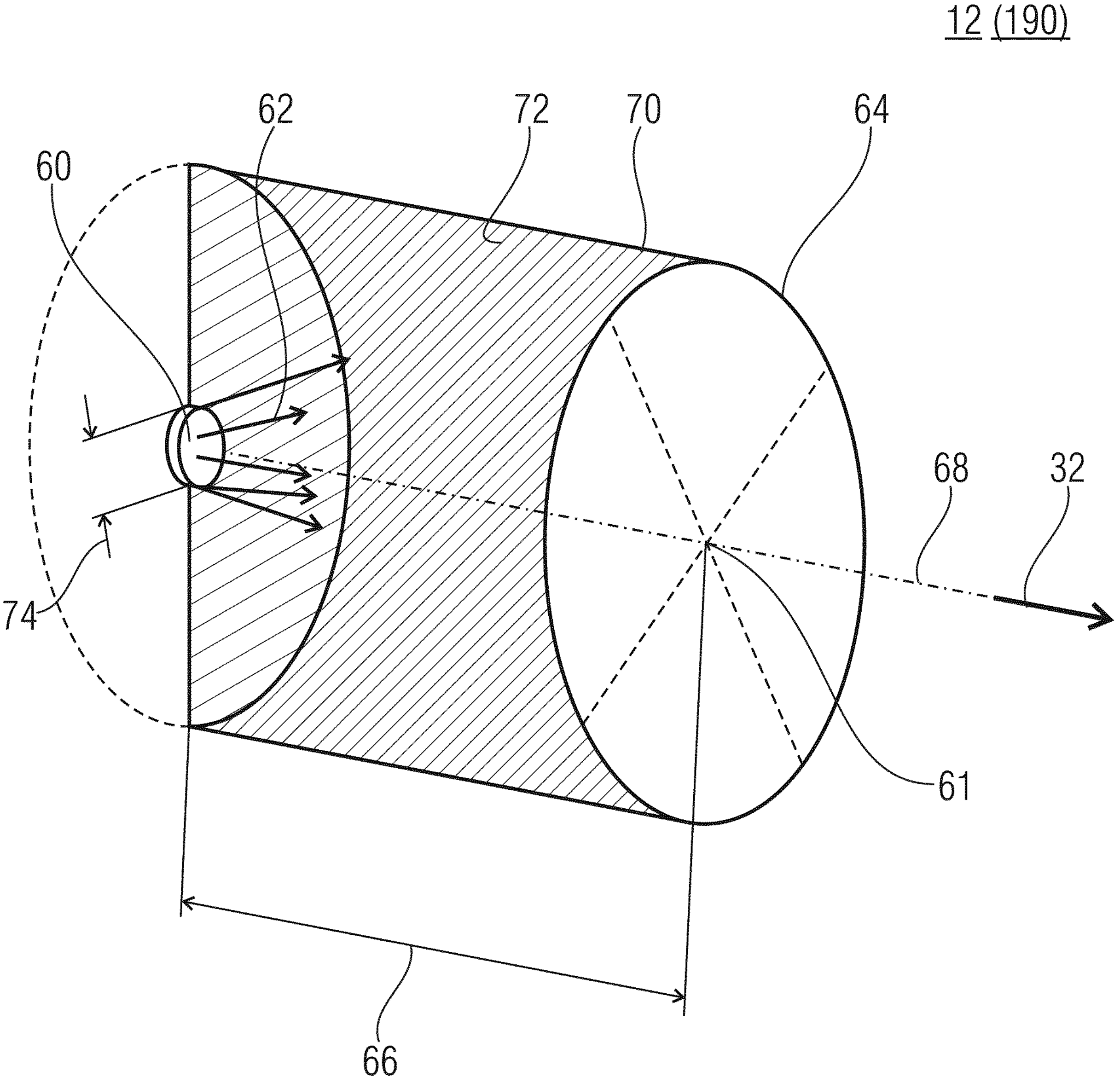


FIG 4

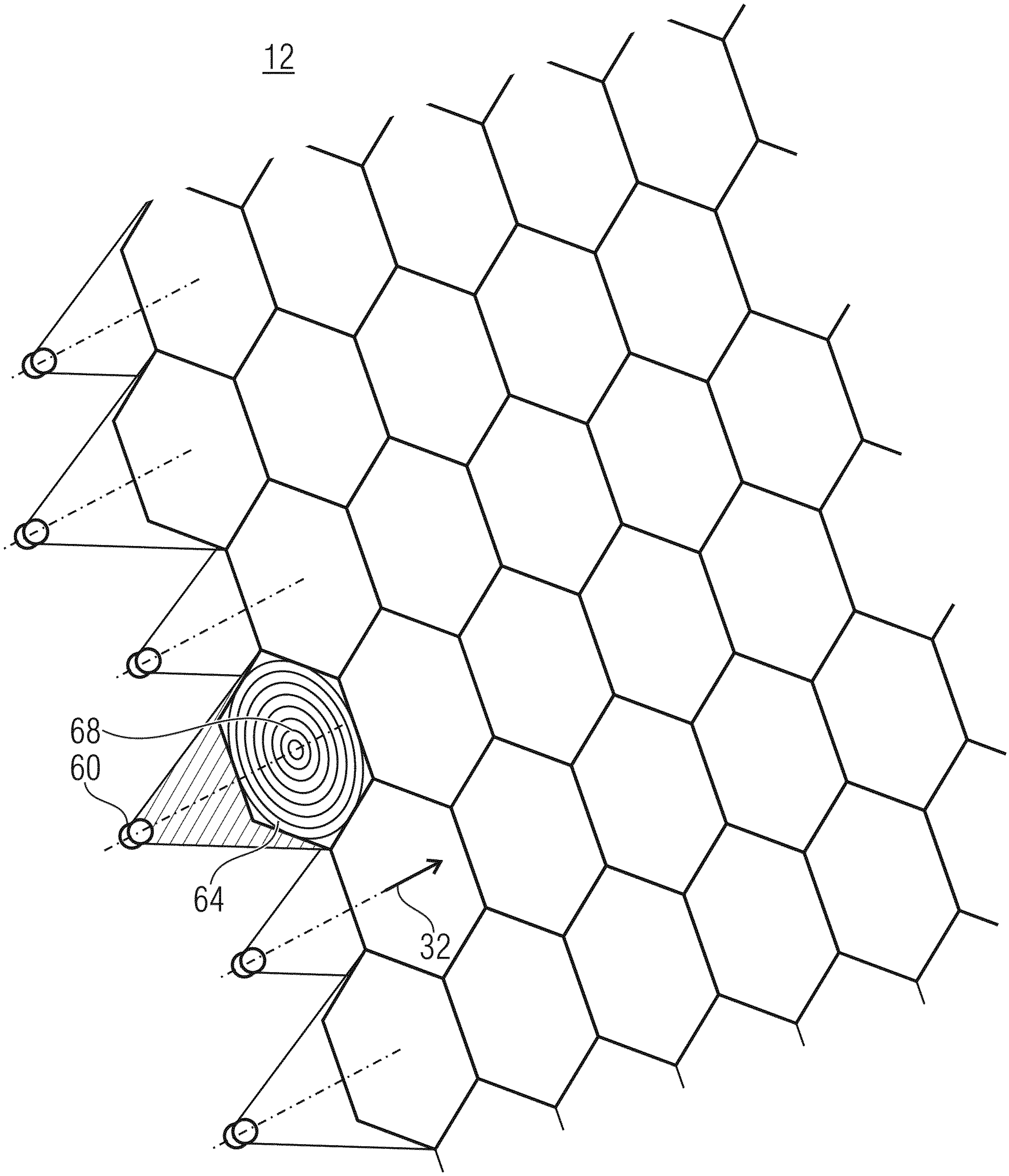


FIG 5

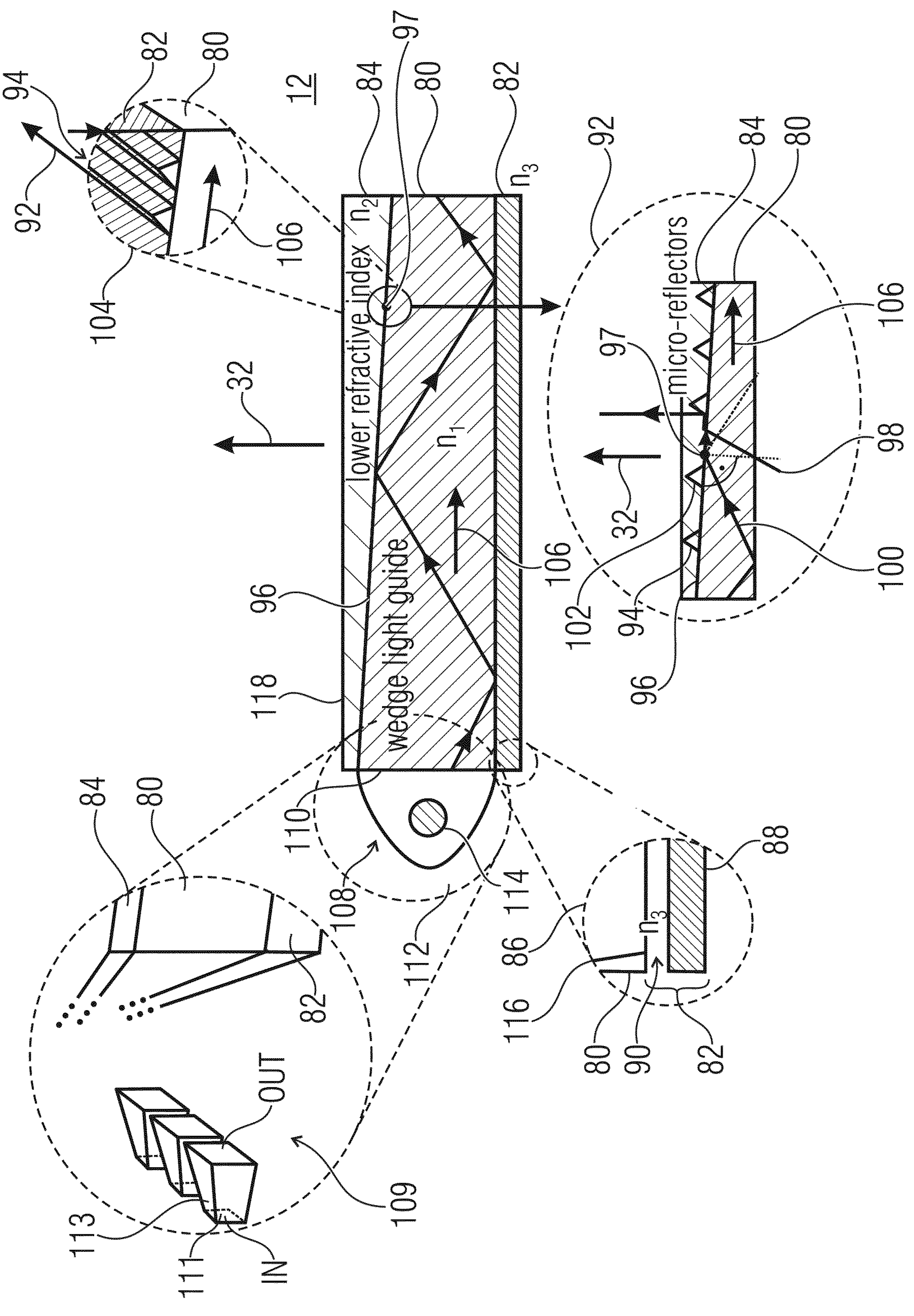

12
32
lower refractive index
wedge light guide
micro-reflectors
n_1
n_2
n_3
80
82
84
86
88
90
92
94
96
97
98
100
102
104
106
108
109
110
111
112
113
114
116
118
IN
OUT

FIG 6

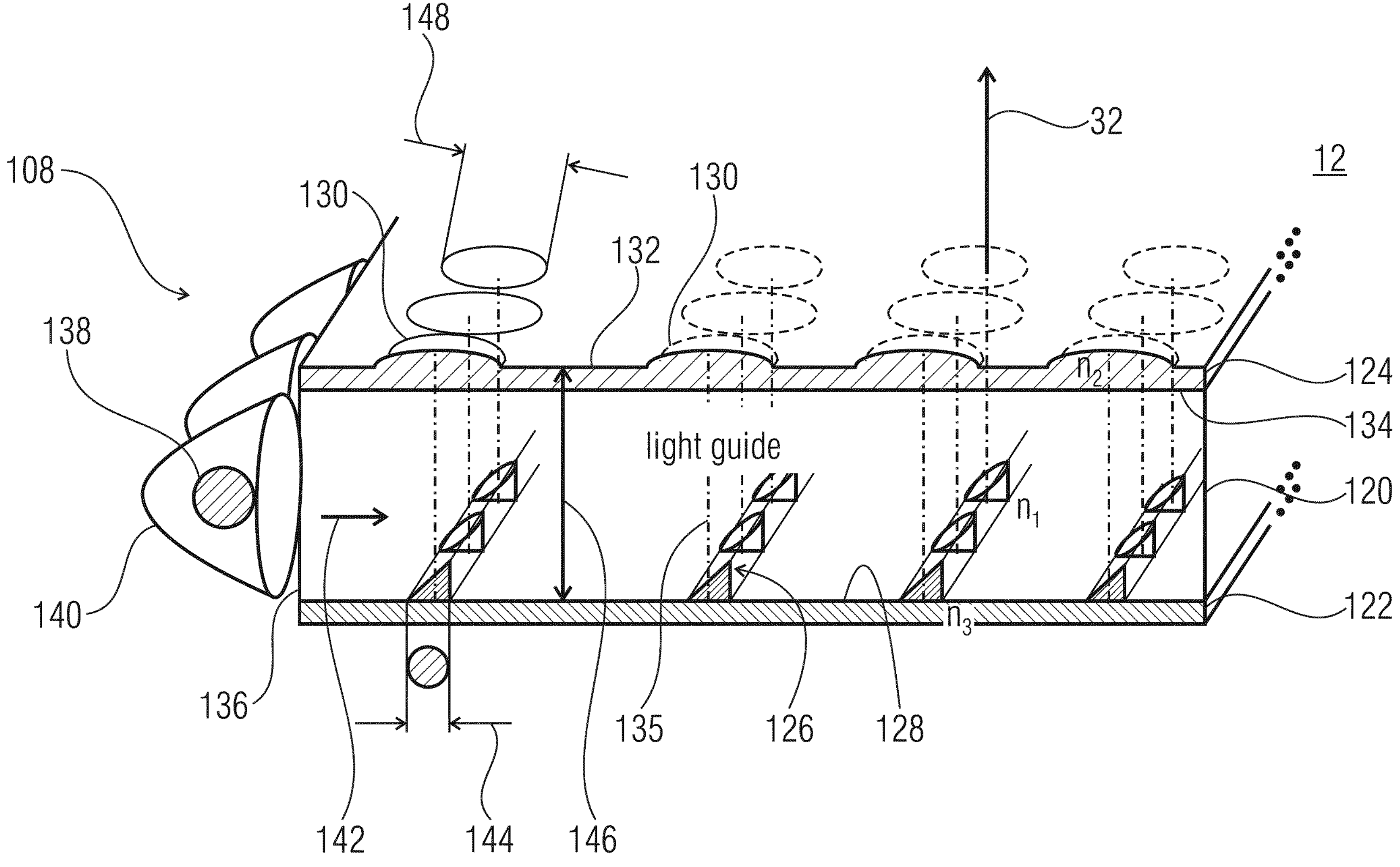

148
108
130
130
132
32
12
138
124
134
light guide
120
n_2
n_1
n_3
140
122
136
135
126
128
142
144
146

FIG 7

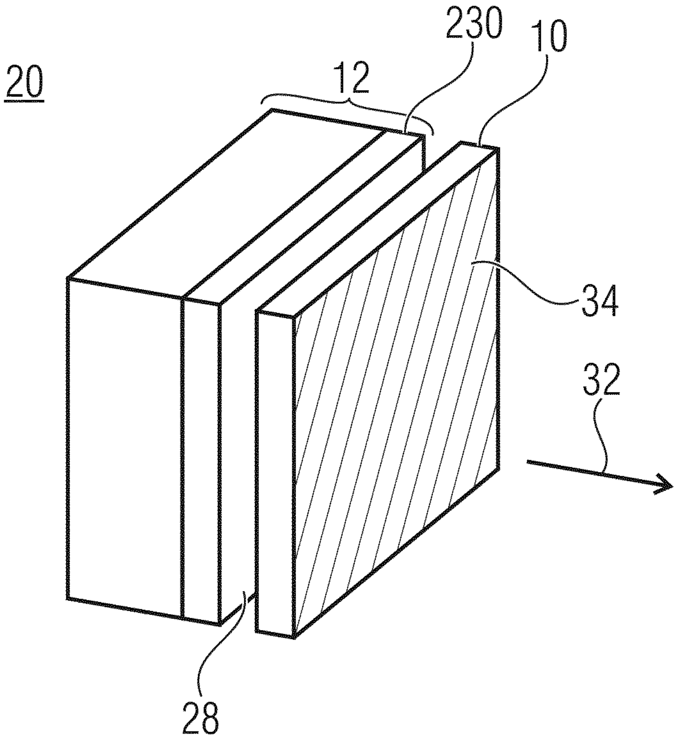


FIG 8

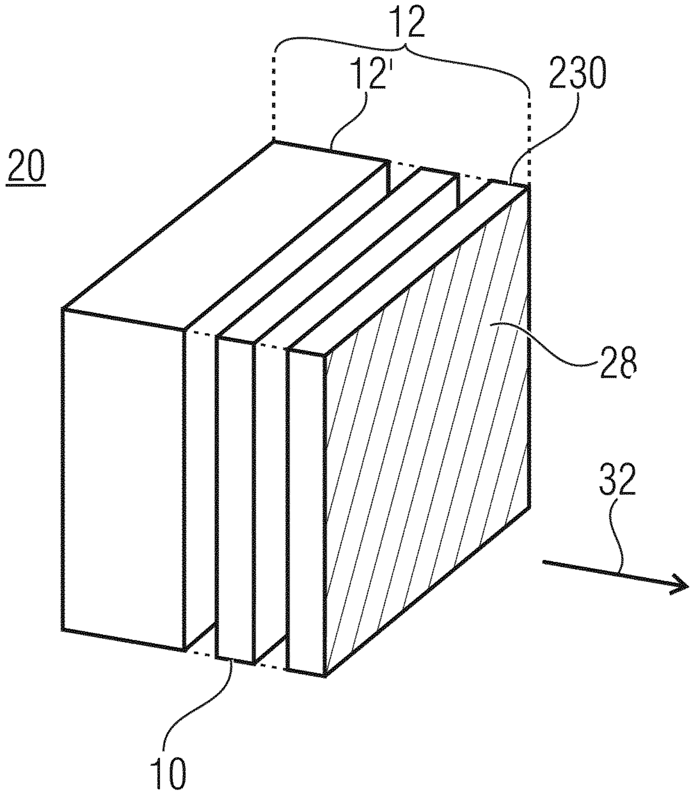


FIG 9

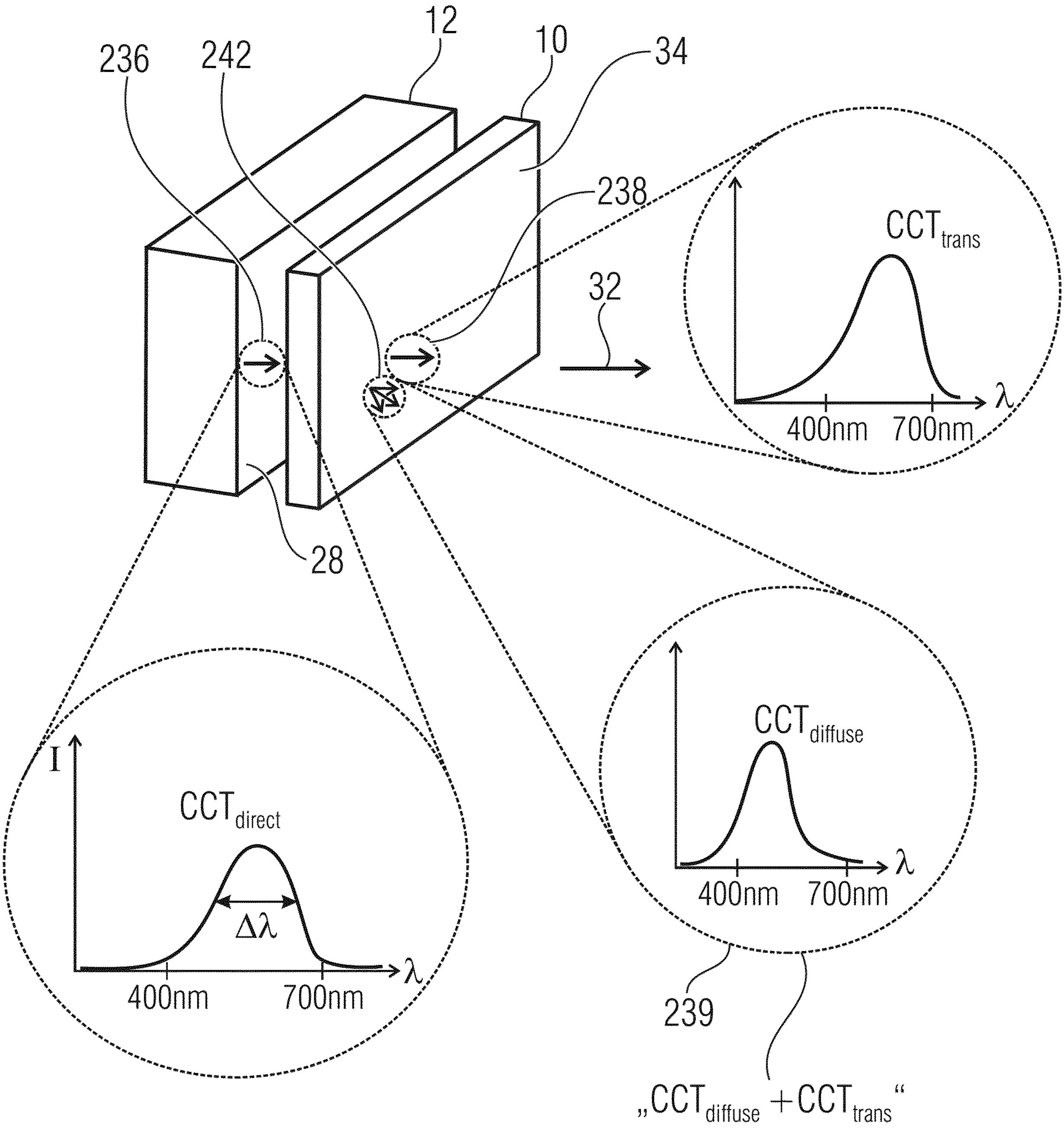

236
242
12
10
34
238
32
28
CCT$_{trans}$
400nm
700nm
λ
I
CCT$_{direct}$
Δλ
400nm
700nm
λ
CCT$_{diffuse}$
400nm
700nm
λ
239
„CCT$_{diffuse}$ + CCT$_{trans}$“

FIG 10A

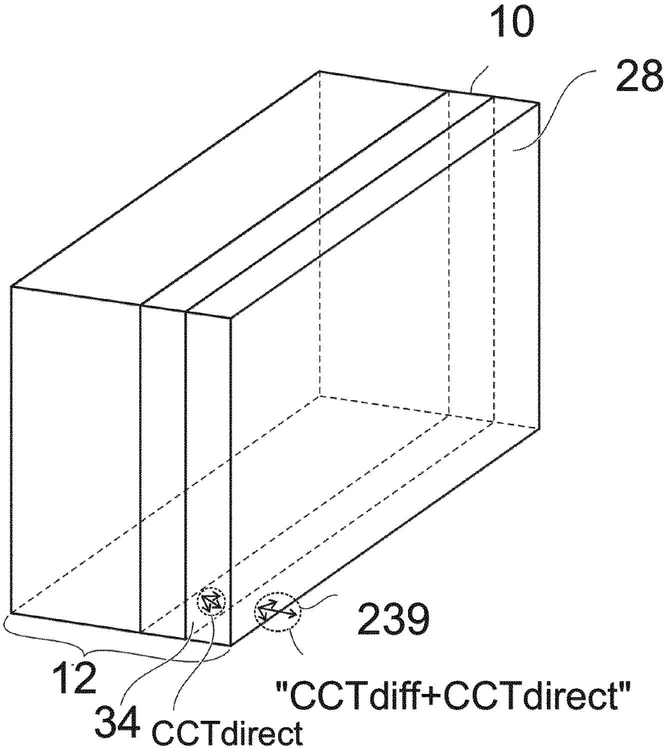


FIG 10B

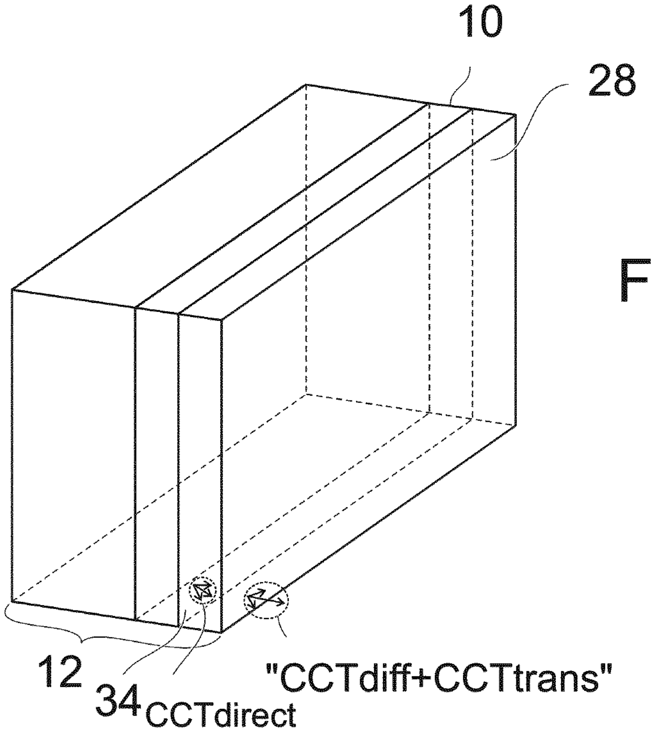


FIG 10C

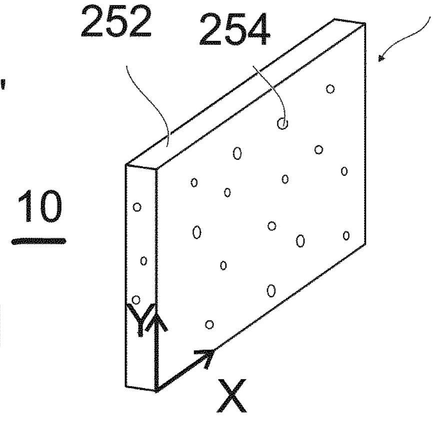


FIG 11

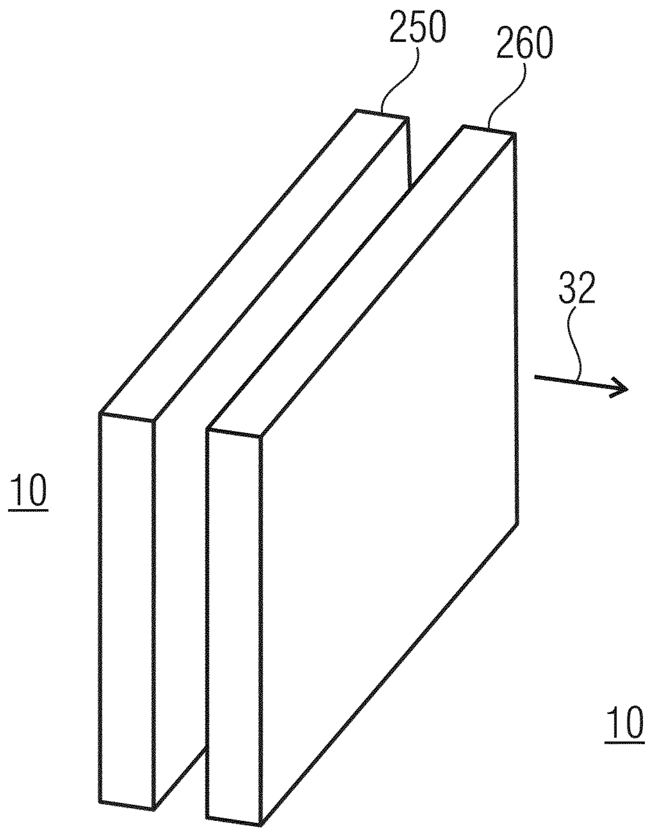


FIG 12A

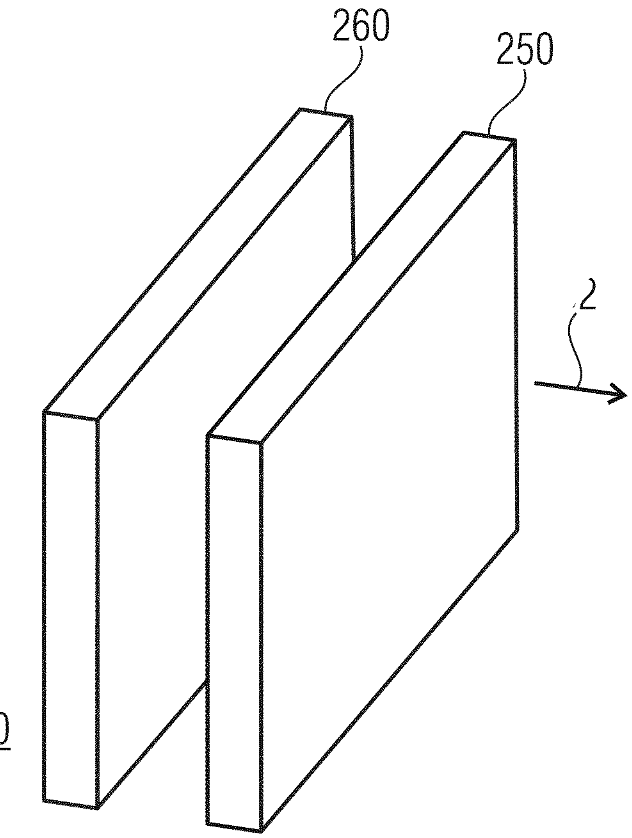


FIG 12B

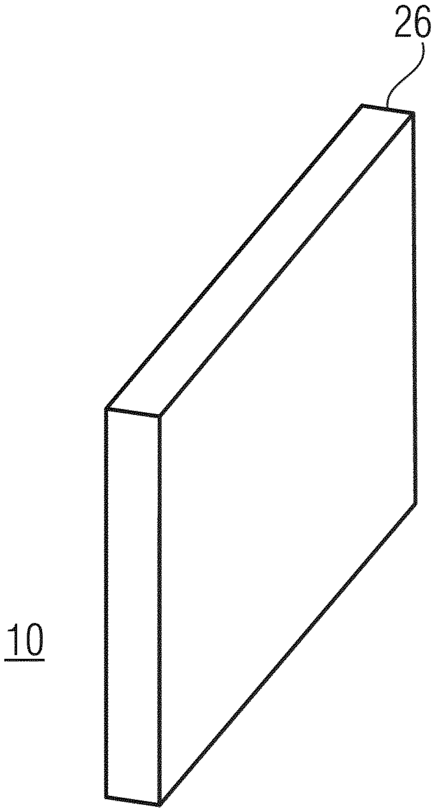


FIG 12C

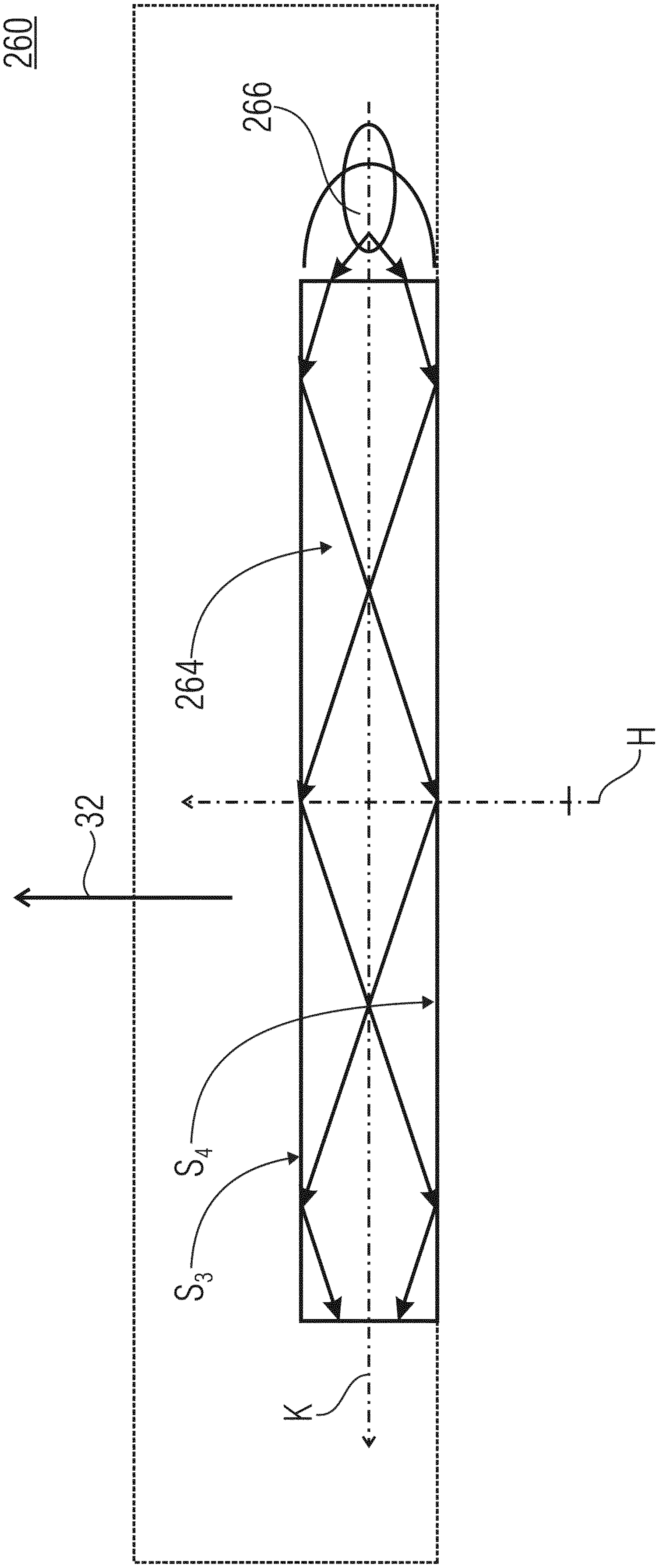


FIG 13

FIG 14A

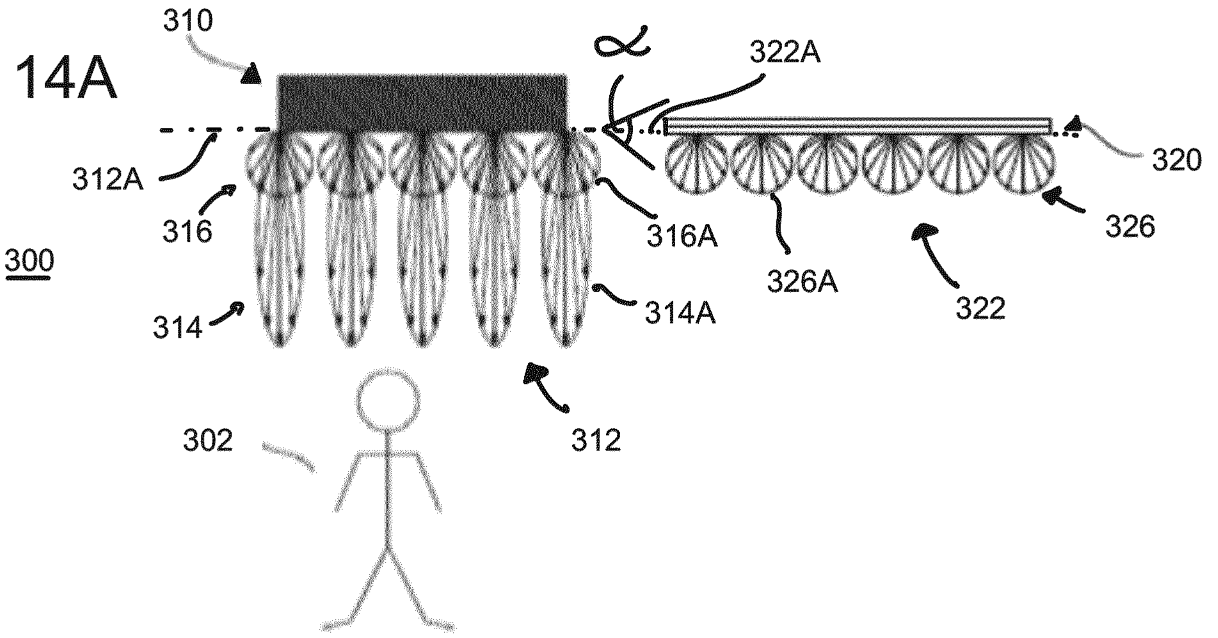


FIG 14B

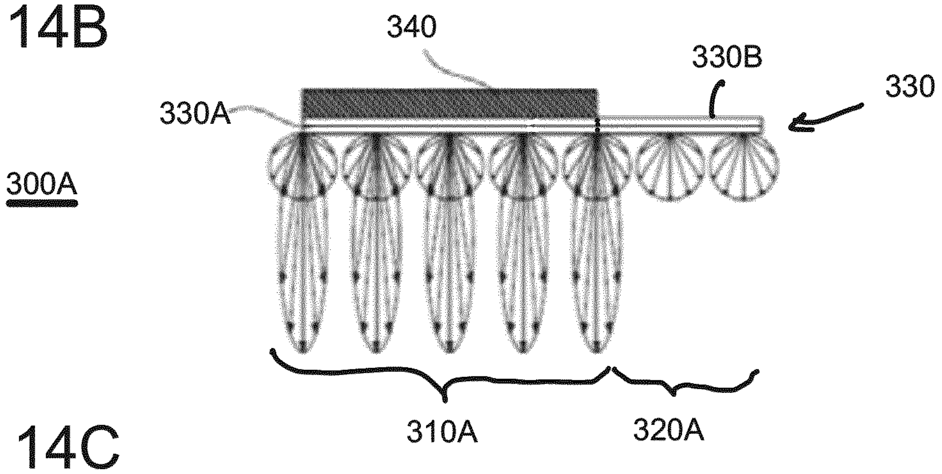


FIG 14C

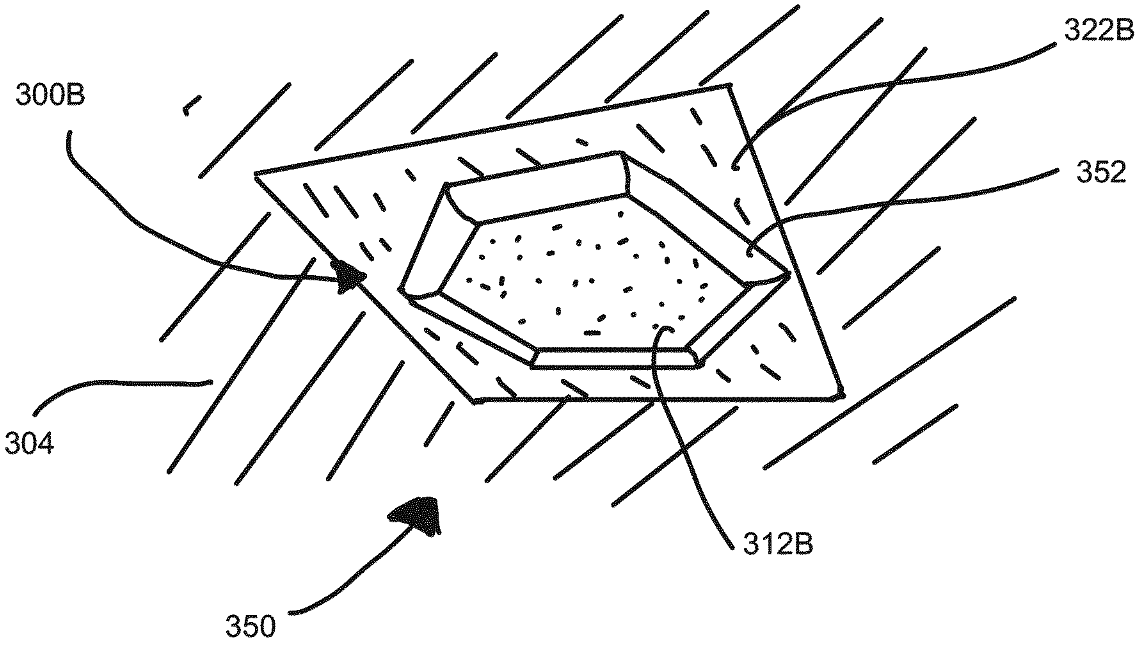


FIG 14D

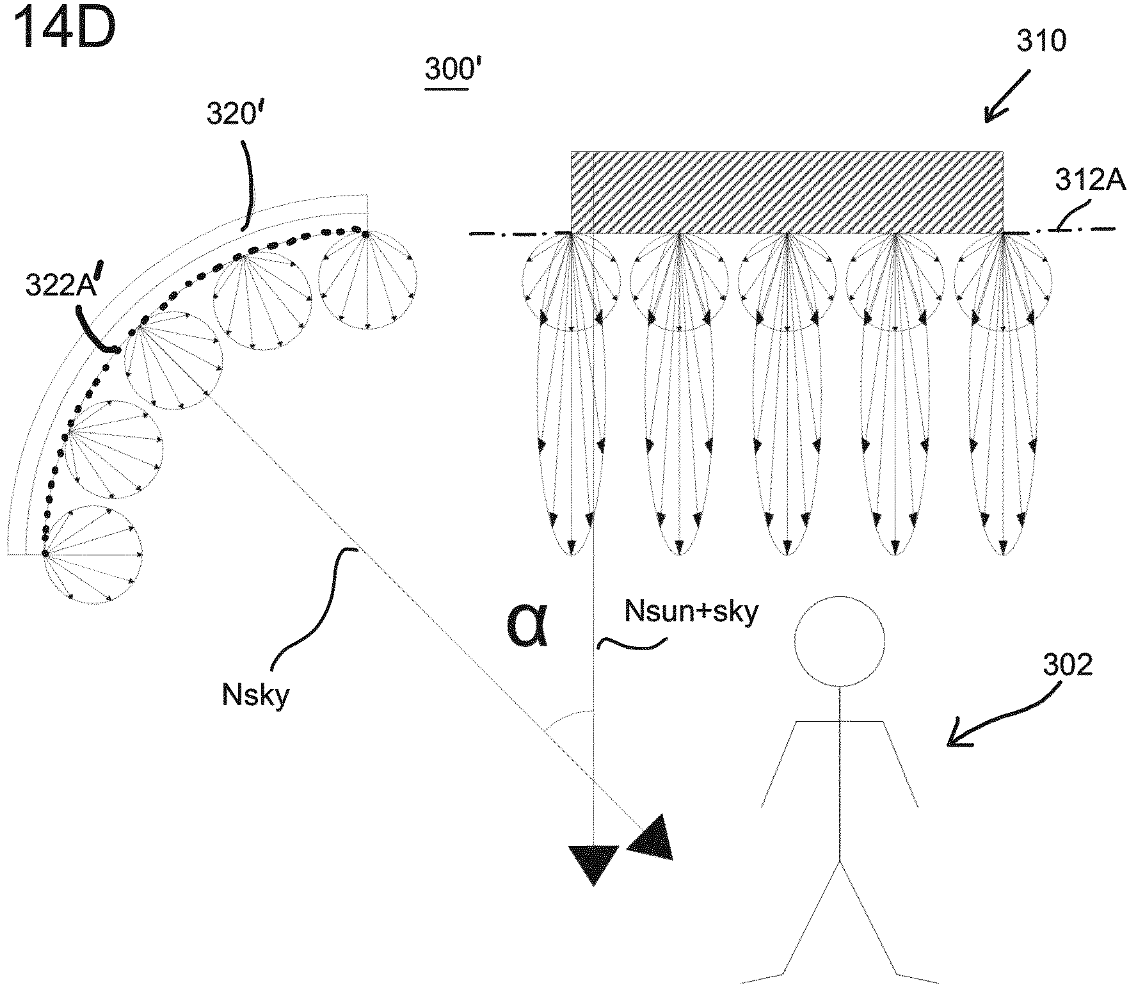


FIG 15

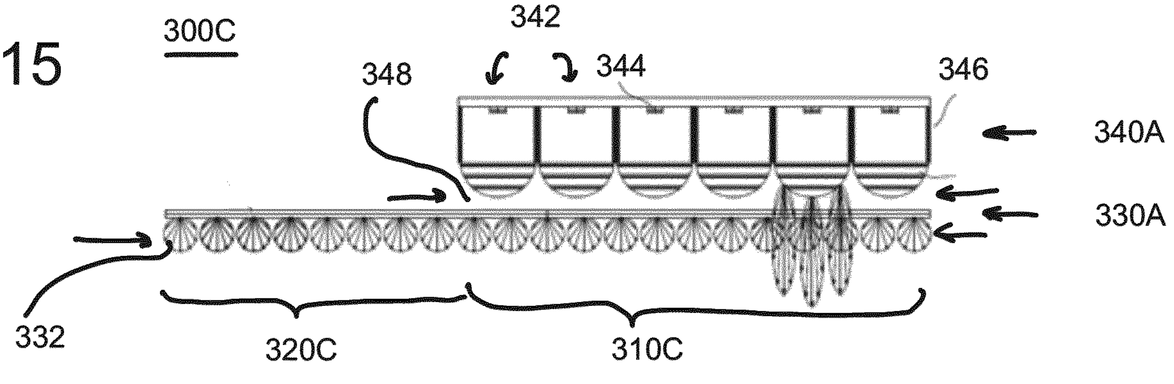


FIG 16A

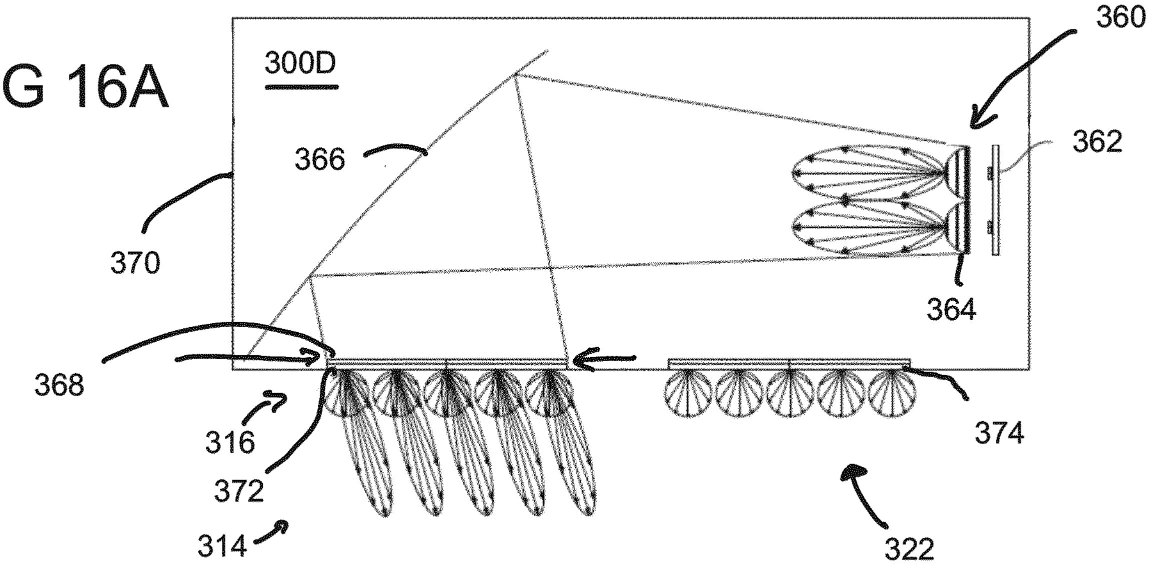


FIG 16B

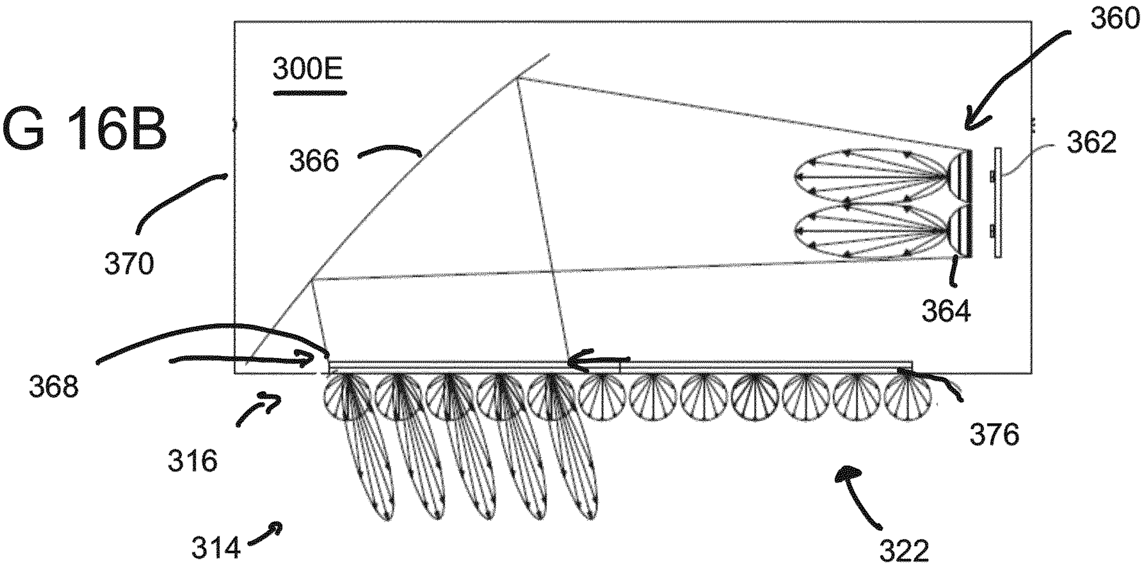


FIG 17A

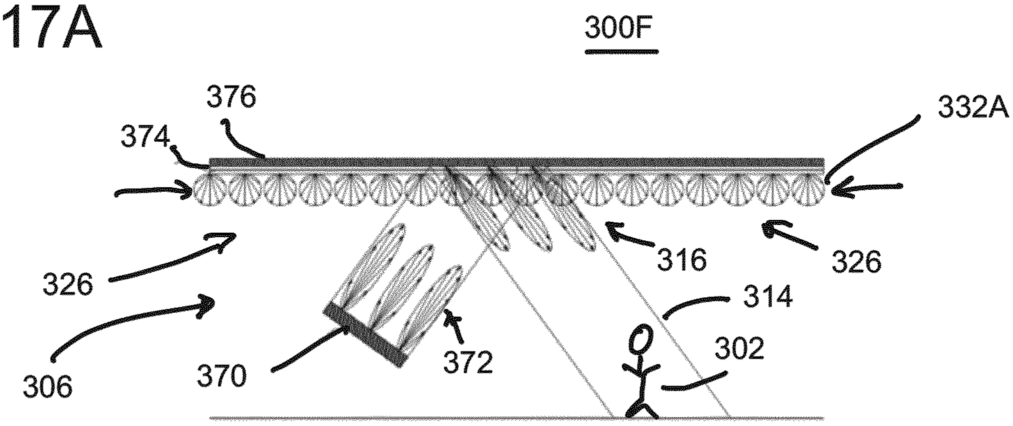


FIG 17B

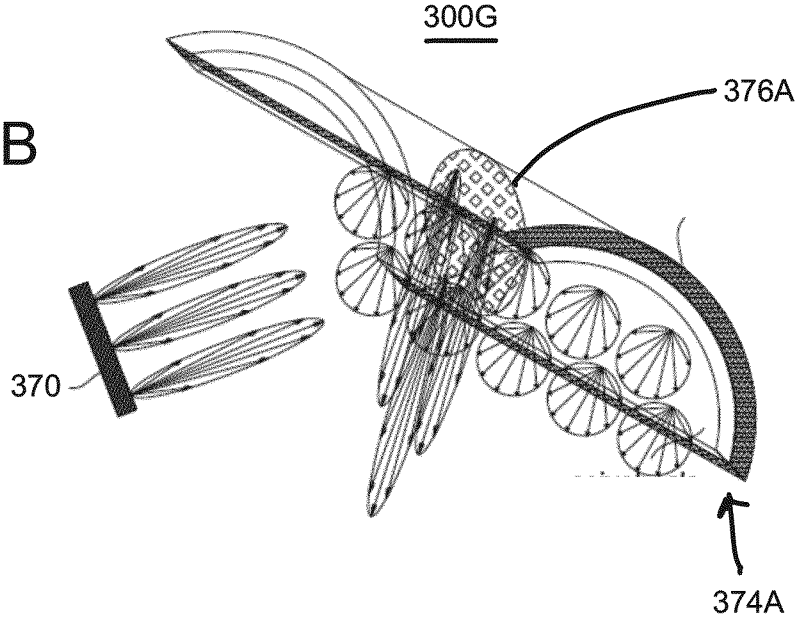


FIG 18A

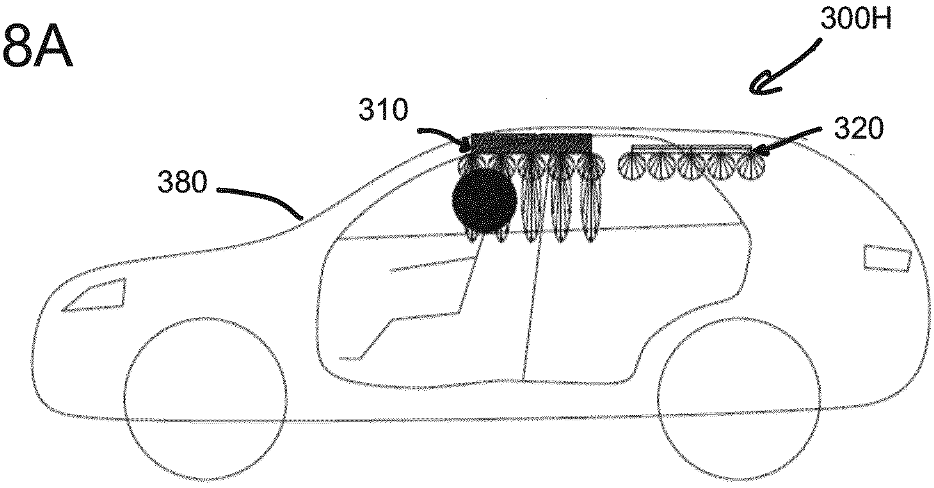


FIG 18B

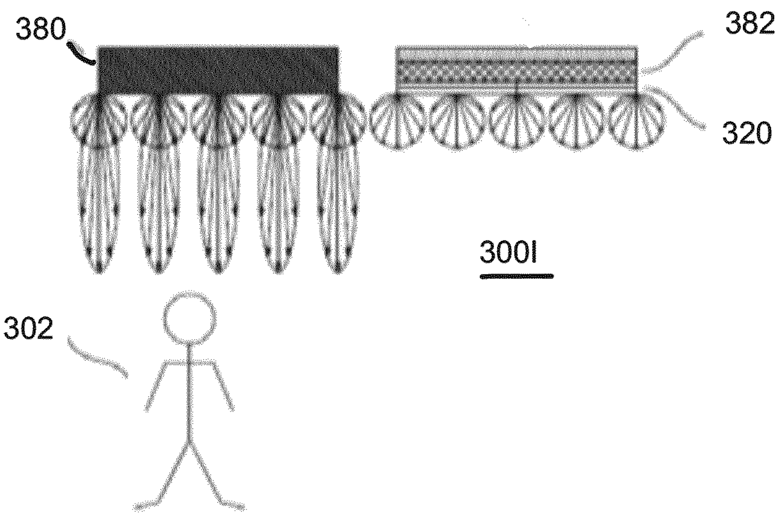
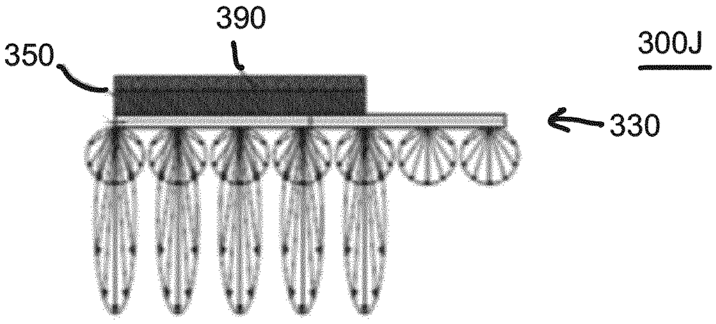


FIG 19


390
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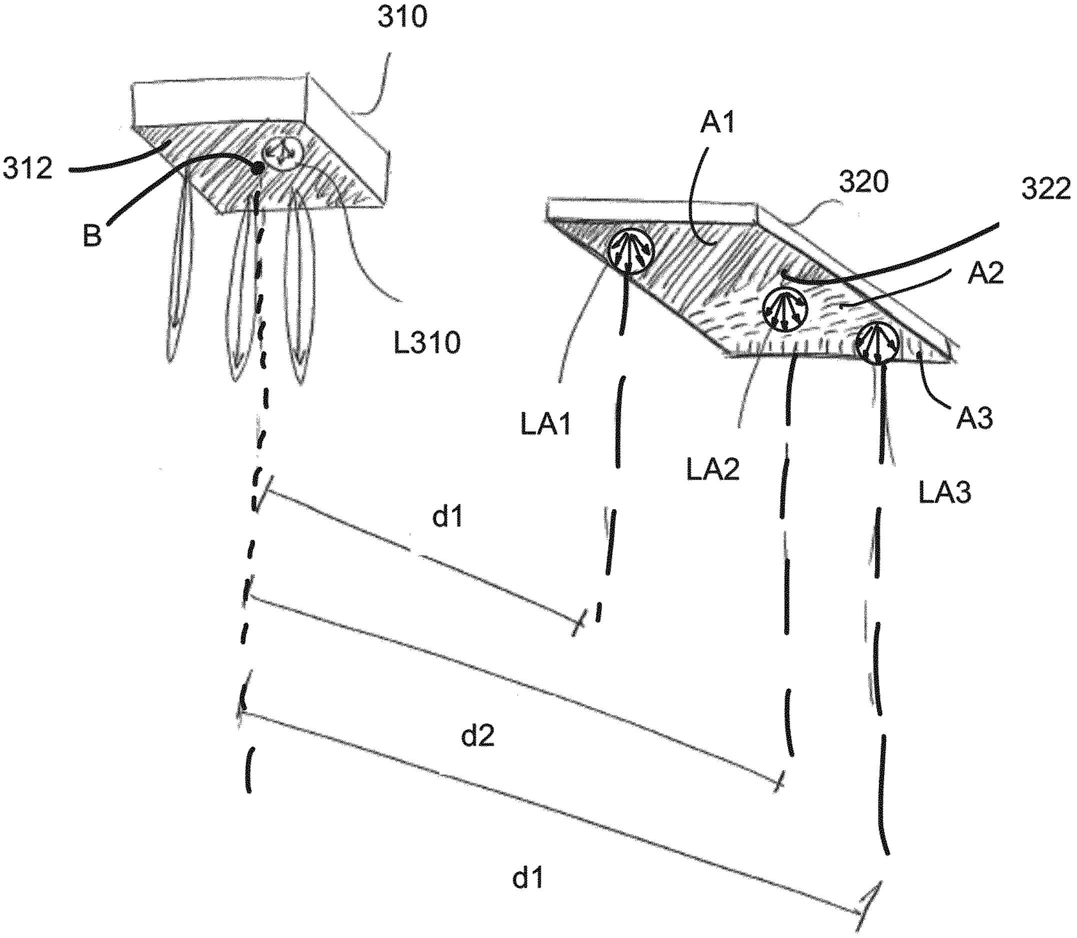
300J
330

FIG 20


310
312
B
L310
A1
320
322
A2
LA1
A3
LA2
LA3
d1
d2
d1

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/076383

A. CLASSIFICATION OF SUBJECT MATTER
INV. F21V9/02 F21V11/08 F21V13/10 F21V7/28
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)
F21S F21V

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

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☒ 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 28 November 2018	Date of mailing of the international search report 11/12/2018
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Dinkla, Remko

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/076383

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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