LIGHT-EMITTING APPARATUS USING METASURFACES AND LIGHT-EMITTING METHOD THEREOF

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of US Provisional Patent Application Serial Nos. 62/862,853, filed June 18, 2019 and 62/961,317, filed January 15, 2020, the content of each of which is incorporated herein by reference in its entirety.

FIELD OF THE DISCLOSURE

The present disclosure relates to light-emitting methods, apparatuses, and systems, and in particular to light-emitting methods, apparatuses, and systems using metasurfaces for controlling the emitted lights.

BACKGROUND

Light-Emitting Diodes (LEDs) are known and have been widely used in many industries, mostly as low-power light indicators. In recent years, LEDs with increased power output or increased luminous intensity have been developed and used as the light source for illumination. For example, with improved energy efficiency, safety, and reliability, LED lights are replacing other types of lights in the market such as incandescent lights, Compact Fluorescent Lamps (CFLs), and the like. As everyday lighting significantly contributes to the burden on power grids and greatly increases the overall requirements for electricity generation, the energy efficiency of LEDs will play a crucial role in future energy savings. It is likely that LEDs will dominate the lighting markets because of their superior energy efficiency.

High-efficient LEDs have been replacing the conventional lighting solutions in a variety of applications such as flashlights, portable lights, lamps, streetlights, and the like. LEDs may be powered by various types of power sources such as batteries, conventional power grids, renewable energy systems and energy storage systems e.g. systems using photovoltaic (PV) panels and battery banks, and the like, thereby providing great flexibility in adapting lighting solutions to specific use scenarios.

In many lighting solutions, it may be preferable to configure the light source such as a LED light source to emit directional light, e.g., to form a convergent beam and focus onto a predefined area for obtaining an enhanced illumination intensity, to form a collimated beam for reaching a target at distance, to form a divergent beam for illuminating a large area, and/or the like. In some lighting solutions, the light direction of the light source may be preferably adjustable. In prior art, light sources usually use mirrors or reflective surfaces for forming directional light,

and mechanical means are often used for turning the mirrors or reflective surfaces to adjust the light direction. Such directional-lighting means are usually of relatively large size, slow responsive, and less efficient.

LEDs with increased power output and/or increased luminous intensity have also been used as light sources for growing plants and the like. Such LEDs, which are sometimes called LED grow lights, provide various advantages such as producing precise wavelengths of lights, high intensity, high efficiency, and the like. LED grow lights are also advantageous for indoor plant growing as the process of growing plants can be performed in controlled environments with much less risks and other unwanted outdoor variables.

The plant growth occurs as a result of "photosynthesis" processes. As known in the art, the photosynthesis processes convert carbon dioxide (CO_2) into organic materials using energy from the light. Specifically, the optical energy is absorbed through special proteins containing chlorophyll pigments that exist in photosynthetic cell membranes called chloroplasts. The photosynthetic cells are mainly in plant leaves.

However, chlorophyll only absorbs energy from particular parts or colors of the light spectrum. The effective spectra are across the blue and red color spectra. The green part of the light spectrum is reflected, which is why plant leaves are usually in green color. When photosynthetic cells in leaves die and the chlorophyll is degraded, other pigmented molecules in the leaves dominate light reflection while they are degraded to the point where the leaves only exhibit brown colors.

Thus, it is known that different pigments in chloroplasts absorb specific wavelengths of light to contribute to photosynthesis, and the photosynthetic efficiency or rate has strong correlation with the spectrum of illumination.

For example, rice plants grown under blue and red illumination have higher photosynthesis efficiency than those grown under only red illumination. Pea leaves grown under red LED light contain higher levels of β-carotene than those grown under blue or white LED light.

Light intensity is another influential factor in photosynthesis due to the response of photosynthesis organisms to high-light intensity to reduce stress effects. Under red LED light, wheat seedlings accumulate chlorophyll at 100 $\mu mol\ m^{-2}\ s^{-1}$, but not at 500 $\mu mol\ m^{-2}\ s^{-1}$.

It is observed that plants usually absorb the blue light spectra during their early growth, and then increasingly absorb the red light spectra as they mature and during their blooming phase. It is also observed that some plants have highly ordered constituents that make their interactions with light polarization sensitive. For example, such plants may more efficiently absorb or reflect light with a specific polarization state than light with other polarization states.

In addition, plants are capable of sensing duration of lighting period and time, and change their growth rates accordingly.

Plant cultivation using constant or universally defined illumination configuration is neither energy efficient nor optimal for photosynthesis. As prior-art LED grow lights usually provide light for the plants without consideration for the aforementioned factors, they fail to provide optimized lighting configurations for optimizing the physiological processes of growing plants. Moreover, different plants require different light characteristics (for example, intensity, spectrum, polarization, time, and the like) to achieve the best growth performance. However, prior-art LED grow lights fail to adapt to the plant needs and fail to provide appropriate light characteristics.

For example, conventional illumination systems such as LED panels used for indoor plant growth usually do not produce a uniform distribution of light over the plants. They often have intensities strongest at the center and increasingly diminishing away from the center.

FIG. 1A shows a conventional light source 10 emitting a light beam 12 towards a square image plane 14 at a distance thereto. FIG. 1B shows the light-intensity distribution 16 on the image plane 14. As can be seen, the conventional light source 10 does not produce a uniform distribution of light on the image plane 14. Rather, the light-intensity distribution 16 on the image plane 14 is strongest at the center thereof and gradually diminishing away from the center. Moreover, the intensity light distribution 16 is symmetric about the incidence point of the light beam 12 on image plane 14.

FIGs. 2A and 2B show the illumination pattern that an LED panel 10 produces in a 6×6 square-meters (m^2) image plane 14 about 3 meters (m) away from the panel 10, obtained using ray-tracing. The intensity distribution is clearly non-uniform.

Therefore, a grow light using such a light source 10 that provides sufficient light in the plant periphery would cause over-illumination at the center of the plant thereby leading to poor plant growth. On the other hand, providing sufficient lighting in the plant center would cause inefficient lighting at the plant periphery, also leading to poor plant growth. Such an intensity distribution is due to symmetry of the image plane center with respect to the light emitters.

Such a light source 10 may not be desirable in other applications. For example, a street light using such a light source 10 may cause glares and overall inefficient illumination.

LEDs are also used for indoor and outdoor displays which also require deliberate control of various light characteristics such as intensity, polarization, time, and/or the like with fast response.

Therefore, it is always a desire for a LED apparatus, system, and method with controlled light characteristics.

SUMMARY

According to a first aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light; and an optical-transformation layer coupled to the light-emitting layer, the optical-transformation layer comprising one or more optical-transformation units, each optical-transformation unit comprising a metasurface for adjusting one or more parameters of the light emitted from the light-emitting layer, wherein the light-emitting layer comprises one or more light-emitting units; wherein the optical-transformation layer comprises a housing comprising one or more receptacles for receiving the one or more metasurfaces; and wherein the one or more receptacles are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

In some embodiments, the light-emitting layer comprises one or more Light-Emitting Diodes (LEDs) for emitting light.

In some embodiments, the optical-transformation layer is printed onto the light-emitting layer.

In some embodiments, the light-emitting layer comprises one or more light-emitting units; the optical-transformation layer comprises a housing having one or more receptacles for receiving the one or more metasurfaces; and the one or more receptacles are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

In some embodiments, each of the one or more receptacles comprises an outwardly expanding inner surface having an inner opening for receiving light emitted from the light-emitting layer and an outer opening for passing through the received light, the outer opening having an area greater than that of the inner opening.

In some embodiments, the inner surface of each of the one or more receptacles is reflective.

In some embodiments, the cross-section of the inner surface of each of the one or more receptacles has a paraboloid shape.

According to a second aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light towards a source field of view (FOV); and an at least one optical-transformation layer comprising at least one metasurface unit in front of the light-emitting layer; and a polarization-control layer sandwiched between the light-emitting layer and the at least one optical-transformation layer; wherein the polarization-control layer is configured for, in response to a control signal, polarizing the light emitted from the light-emitting layer to a first polarization state or to a second polarization state; and wherein the at least one optical-transformation layer is configured for directing the light from the polarization-control layer in the first polarization state towards a first FOV having an angular span smaller than that of the source FOV, and directing the light from the polarization-control

layer in the second polarization state towards a second FOV having an angular span greater than that of the first FOV.

In some embodiments, each of the one or more metasurfaces comprises a plurality of nano-scale structures arranged in an asymmetric base geometry.

In some embodiments, the light-emitting apparatus further comprises a polarization-control layer sandwiched between the light-emitting layer and the optical-transformation layer for polarizing the light emitted from the light-emitting layer.

In some embodiments, the light-emitting apparatus is a grow light for facilitating the growth of one or more plants.

According to a third aspect of this disclosure, there is provided a light-emitting apparatus for facilitating the growth of one or more plants. The light-emitting apparatus comprises: a light-emitting layer for emitting light; and at least one optical-transformation layer comprising one or more optical-transformation units, each optical-transformation unit comprising a metasurface for adjusting one or more parameters of the light emitted from the light-emitting layer for optimizing illumination configurations of the one or more plants, wherein the light-emitting layer comprises one or more light-emitting units; wherein the optical-transformation units are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

According to a fourth aspect of this disclosure, there is provided a display apparatus. The display apparatus comprises: a light-emitting layer for emitting light; and at least one optical-transformation layer comprising one or more optical-transformation units, each optical-transformation unit comprising a metasurface for adjusting one or more parameters of the light emitted from the light-emitting layer for displaying one or more images, wherein the light-emitting layer comprises one or more light-emitting units; wherein the optical-transformation units are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

According to a fifth aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light; a polarization-control layer coupled to the light-emitting layer for polarizing the light emitted from the light-emitting layer; and at least one optical-transformation layer coupled to the polarization-control layer, the at least one optical-transformation layer comprising one or more optical-transformation units, each optical-transformation unit comprising at least one metasurface, at least one metasurface being polarization-selective for selectively passing therethrough the polarized light from the polarization-control layer for switching between different illumination patterns or images, wherein the light-emitting layer comprises one or more light-emitting units; wherein the optical-transformation units are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

According to a sixth aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light; a polarization-control layer coupled to the light-emitting layer for polarizing the light emitted from the light-

emitting layer; and at least one optical-transformation layer coupled to the polarization-control layer, the at least one optical-transformation layer comprising one or more optical-transformation units, each optical-transformation unit comprising at least one metasurface, at least one metasurface being polarization-selective for selectively passing therethrough the polarized light from the polarization-control layer for creating multiple different illumination patterns or images at different locations, wherein the light-emitting layer comprises one or more light-emitting units; wherein the optical-transformation units are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

According to a seventh aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light towards a source field of view (FOV); and at least one metasurface layer in front of the light-emitting layer for directing the light emitted from the light-emitting layer towards a first FOV having an angular span smaller than that of the source FOV.

In some embodiments, the light-emitting apparatus further comprises a polarization-control layer sandwiched between the light-emitting layer and the at least one optical-transformation layer; the polarization-control layer is configured for, in response to a control signal, polarizing the light emitted from the light-emitting layer to a first polarization state or to a second polarization state; and wherein the at least one optical-transformation layer is configured for directing the light from the polarization-control layer in the first polarization state towards a first FOV having an angular span smaller than that of the source FOV, and directing the light from the polarization-control layer in the second polarization state towards a second FOV having an angular span greater than that of the first FOV.

According to an eighth aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light; and an optical-transformation layer in front of the light-emitting layer, the optical-transformation layer comprising a plurality of optical-transformation units, each optical-transformation unit comprising a metasurface for directing light emitted from the light-emitting layer towards a target area for forming a predefined light-distribution pattern, wherein the light-emitting layer comprises one or more light-emitting units; wherein the optical-transformation units are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

In some embodiments, the predefined light-distribution pattern is a substantively uniform optical-energy distribution on the target area.

In some embodiments, the plurality of metasurfaces comprise a first set of metasurfaces for directing the light emitted from the light-emitting layer towards borders of the target area, and a second set of metasurfaces for directing the light emitted from the light-emitting layer towards a center of the target area, for generating the substantively uniform optical-energy distribution on the target area.

According to a ninth aspect of this disclosure, there is provided a solar-energy harvesting apparatus. The solar-energy harvesting apparatus comprises: a photovoltaic layer having a plurality of photovoltaic cells; and at least one metasurface layer in front of the photovoltaic layer for directing light to the photovoltaic layer substantively without causing reflection on the photovoltaic layer.

In some embodiments, the solar-energy harvesting apparatus comprises a plurality of metasurface layers for directing light at an incident angle within a predefined range to perpendicularly imping the photovoltaic layer.

According to a tenth aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light; and at least one optical-transformation layer comprising at least one metasurface layer in front of the light-emitting layer for directing the light emitted from the light-emitting layer in a first polarization state towards a first FOV and directing the light emitted from the light-emitting layer in a second polarization state towards a second FOV; the first and second FOVs are overlapped and laterally offset from each other for forming a three-dimensional (3D) perception to a user wearing a pair of glasses with lenses of different polarization states.

According to an eleventh aspect of this disclosure, there is provided a light-emitting apparatus. The light-emitting apparatus comprises: a light-emitting layer for emitting light; and at least one metasurface layer in front of the light-emitting layer for directing the light emitted from the light-emitting layer in a first polarization state towards a first FOV and directing the light emitted from the light-emitting layer in a second polarization state towards a second FOV; the first and second FOVs are laterally offset from each other such that the first FOV is only viewable to a first eye of a user at a predefined distance and the second FOV is only viewable to a second eye of the user at the predefined distance, for forming a 3D perception to the user.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a schematic diagram showing a prior-art light source emitting a light beam towards a square image plane at a distance thereto;

FIG. 1B shows the light-intensity distribution on the image plane of the light emitted from the prior-art light source shown in FIG. 1A;

FIG. 2A is a schematic diagram showing a prior-art Light-Emitting Diode (LED) panel emitting a light beam towards a square image plane at a distance thereto;

FIG. 2B shows the illumination pattern on the image plane of the light emitted from the prior-art LED panel, obtained using ray-tracing;

FIG. 3 is a schematic diagram showing the structure of a lighting-emitting apparatus, according to some embodiments of this disclosure, the lighting-emitting apparatus comprising a LED light-emitting layer and an optical-transformation layer having one or more metasurfaces;

FIG. 4 is a schematic exploded view of the lighting-emitting apparatus shown in FIG. 3;

FIG. 5 shows an optical-transformation unit of an optical-transformation layer of the lighting-emitting apparatus shown in FIG. 3;

FIG. 6 shows an example of the structure of a metasurface for forming the optical-transformation unit shown in FIG. 5;

FIG. 7 is a schematic exploded view of a lighting-emitting apparatus, according to some embodiments of this disclosure, the lighting-emitting apparatus comprising a LED light-emitting layer, a polarization-control layer, and a metasurface optical-transformation layer;

FIG. 8A is a schematic diagram showing a pixel of the polarization-control layer of the light apparatus shown in FIG. 7, according to some embodiments of this disclosure;

WHAT IS CLAIMED IS:

1. A light-emitting apparatus comprising:

a light-emitting layer for emitting light; and

an optical-transformation layer coupled to the light-emitting layer, the optical-transformation layer comprising one or more optical-transformation units, each optical-transformation unit comprising a metasurface for adjusting one or more parameters of the light emitted from the light-emitting layer;

wherein the light-emitting layer comprises one or more light-emitting units;

wherein the optical-transformation layer comprises a housing comprising one or more receptacles for receiving the one or more metasurfaces; and

wherein the one or more receptacles are at locations corresponding to those of the one or more light-emitting units for aligning the one or more metasurfaces with the one or more light-emitting units.

2. The light-emitting apparatus of claim 1, wherein the light-emitting layer comprises one or more Light-Emitting Diodes (LEDs) for emitting light.

3. The light-emitting apparatus of claim 1, wherein the optical-transformation layer is printed onto the light-emitting layer.

4. The light-emitting apparatus of claim 1, wherein each of the one or more receptacles comprises an outwardly expanding inner surface having an inner opening for receiving light emitted from the light-emitting layer and an outer opening for passing through the received light, the outer opening having an area greater than that of the inner opening.

5. The light-emitting apparatus of claim 4, wherein the inner surface of each of the one or more receptacles is reflective.

6. The light-emitting apparatus of claim 5, wherein the cross-section of the inner surface of each of the one or more receptacles has a paraboloid shape.

7. A light-emitting apparatus comprising:

a light-emitting layer for emitting light towards a source field of view (FOV);

at least one optical-transformation layer comprising at least one metasurface unit in front of the light-emitting layer; and

a polarization-control layer sandwiched between the light-emitting layer and the at least one optical-transformation layer;

wherein the polarization-control layer is configured for, in response to a control signal, polarizing the light emitted from the light-emitting layer to a first polarization state or to a second polarization state; and

wherein the at least one optical-transformation layer is configured for directing the light from the polarization-control layer in the first polarization state towards a first FOV having an angular span smaller than that of the source FOV, and directing the light from the polarization-control layer in the second polarization state towards a second FOV having an angular span greater than that of the first FOV.

8. A light-emitting apparatus comprising:

a light-emitting layer for emitting light; and

at least one optical-transformation layer comprising at least one metasurface layer in front of the light-emitting layer for directing the light emitted from the light-emitting layer in a first polarization state towards a first FOV and directing the light emitted from the light-emitting layer in a second polarization state towards a second FOV;

wherein the first and second FOVs are overlapped and laterally offset from each other for forming a three-dimensional (3D) perception to a user wearing a pair of glasses with lenses of different polarization states.

9. A light-emitting apparatus comprising:

a light-emitting layer for emitting light; and

at least one metasurface layer in front of the light-emitting layer for directing the light emitted from the light-emitting layer in a first polarization state towards a first FOV and directing the light emitted from the light-emitting layer in a second polarization state towards a second FOV;

wherein the first and second FOVs are laterally offset from each other such that the first FOV is only viewable to a first eye of a user at a predefined distance and the second FOV is only viewable to a second eye of the user at the predefined distance, for forming a 3D perception to the user.