

DEVICE FOR COLOR CONVERSION AND METHOD FOR FORMING THE SAME**TECHNICAL FIELD**

[0001] The present disclosure generally relates to a device for color conversion and a method for forming a device for color conversion.

BACKGROUND

[0002] Visible semiconductor light-emitting diodes (LEDs), particularly in blue GaN-based and AlGaInP-based red LEDs, have made impressive strides in efficiency, achieving over 80% external quantum efficiency (EQE). However, future applications like microdisplays for virtual and augmented reality require even smaller LEDs, down to a few micrometres, which tend to have lower EQE, especially in the green and red regions. These challenges are compounded by difficulties in assembling millions of tiny microLEDs with high precision onto a display's backplane, especially for full-color displays where accurate placement of red, green, and blue LEDs is critical. Green microLEDs suffer from lower efficiency, red microLEDs face high surface recombination rates, and driving voltage disparities between different colors add complexity to display design. As a result, achieving cost-effective consumer products remains challenging. However, ongoing advancements in materials, manufacturing techniques, and integration processes are promising, with potential solutions including improved materials for higher efficiency, precision assembly technologies like micro-transfer printing, and better thermal management to overcome these barriers.

[0003] The challenges in creating vibrant and efficient full-color displays for microLED applications, such as head-up displays, virtual reality, and augmented reality, become even more pronounced due to the need for high precision in assembling multi-color microLEDs, especially across the RGB spectrum. The traditional "Pick-n-place" method, while widely used, faces significant limitations when it comes to aligning millions of microLEDs accurately and efficiently. This method struggles with issues like misalignment, defects, and the need for fine-tuning the placement of red, green, and blue microLEDs. To address these obstacles, researchers and industry professionals are exploring innovative solutions, such as micro-transfer printing, laser-based assembly, and nanomanufacturing techniques that promise higher precision and scalability. These approaches aim to reduce assembly errors, improve yield rates, and lower production costs, making multi-color microLED displays more viable for next-generation technologies. Additionally, advancements in quantum dot materials and advanced

thermal management are helping to enhance the efficiency and performance of green and red microLEDs, which have traditionally struggled with lower quantum efficiency at smaller scales.

[0004] One promising approach for improving microLED displays is using color-conversion processes, where a single type of microLED, typically blue, is used for all pixels, and quantum dots (QDs) are employed to generate green and red colors. This method enables the creation of an RGB display with fewer types of LEDs, simplifying the design and potentially reducing costs. However, as pixel sizes shrink, traditional methods that rely on thick QD layers become less effective, raising concerns about issues like cross-talk, re-absorption, and inefficient light extraction. As the pixel dimensions decrease, the light emitted by the blue microLED can become trapped or absorbed by the QDs, leading to loss of efficiency and color quality. Additionally, efficient color conversion faces challenges related to weak out-coupling of guided modes, which makes it difficult to direct the light out of the device efficiently. Furthermore, the QD layer can degrade over time, potentially impacting the overall performance and lifespan of the display. Addressing these complex issues requires innovative strategies, such as thinner QD layers, advanced out-coupling techniques, and the development of more stable and efficient QDs that can maintain their performance over time, helping microLED displays achieve both high efficiency and vibrant color conversion as the technology evolves.

[0005] Therefore, there exists a need to provide an improved device for color conversion.

SUMMARY

[0006] According to a first aspect of the present disclosure, a device for color conversion is provided. The device may include: a substrate; and a plurality of nanostructures disposed over the substrate, wherein the plurality of nanostructures includes a first dielectric layer with a first refractive index and a second dielectric layer with a second refractive index, the first refractive index being different from the second refractive index.

[0007] According to a second aspect of the present disclosure, a method for forming a device for color conversion is provided. The method may include: forming a second dielectric layer with a second refractive index over a substrate; forming a first dielectric layer with a first refractive index on the second dielectric layer; forming a plurality of nanostructures based on the second dielectric layer and the first dielectric layer using photolithography, wherein the first refractive index is different from the second refractive index.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 is a block diagram showing a cross-sectional view (in x-z plane) of a device 10 according to various embodiments of the present disclosure.

[0009] FIGS. 2A and 2B show exemplary examples of the device of FIG. 1.

[0010] FIG. 3A is a block diagram showing a cross-sectional view (in the x-z plane) of a device according to various embodiments of the present disclosure; FIG. 3B is a block diagram showing a cross-sectional view (in the x-z plane) of another device according to various embodiments of the present disclosure.

[0011] FIG. 4A shows a block diagram showing a perspective view of a DBR structure; FIG. 4B show the average reflection of the DBR structure of FIG. 4A as a function of the incident angle and wavelength of incident light; FIG. 4C shows the average absorption of the DBR structure of FIG. 4A as a function of the incident angle and wavelength of incident light.

[0012] FIG. 5A shows a block diagram showing a perspective view of an optimized DBR structure integrated with a metasurface; FIG. 5B shows the average absorption of the optimized DBR structure of FIG. 5A as a function of the incident angles and the spectrum (λ) according to an embodiment of the present disclosure.

[0013] FIG. 6 shows dispersion bands of the device of FIG. 3A.

[0014] FIG. 7 shows distribution of eigenfields in the central x-y plane of the first/SiO₂ dielectric layer of the device of FIG. 3A.

[0015] FIG. 8 shows distribution of eigenfields in the x-z plane of the device of FIG. 3A, extending to both the first/TiO₂ and second/SiO₂ dielectric layers.

[0016] FIG. 9 is a flowchart showing a method for forming a device for color conversion according to various embodiments of the present disclosure.

[0017] FIG. 10 show an excess removal process according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

[0018] Embodiments described below in the context of a method are analogously valid for the respective element, device, apparatus, or system, and *vice versa*. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment, and a part of one implementation may be combined with a part of another implementation.

[00019] It should be understood that the singular terms "a", "an", and "the" include plural references unless context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise.

[00020] It will be further understood that the terms "comprise" (and any form of comprise, such as "comprises" and "comprising"), "have" (and any form of have, such as "has" and "having"), "include" (and any form of include, such as "includes" and "including"), and "contain" (and any form of contain, such as "contains" and "containing") are open-ended linking verbs. As a result, a method or device that "comprises," "has," "includes" or "contains" one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more steps or elements. Likewise, a step of a method or an element of a device that "comprises," "has," "includes" or "contains" one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

[00021] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about," "substantially", is not limited to the precise value specified but within tolerances that are acceptable for operation of the embodiment for an application for which it is intended. In some instances, the approximating language may correspond to the precision of an instrument for measuring the value.

[00022] The present disclosure seeks to address the inefficiencies of color-conversion processes that affect the development of a wide array of optical devices, such as Light Emitting Device (LED) displays and photon detection platforms. Color conversion is the process of transforming light from one color to another. It involves using specific materials, often quantum dots, to absorb light of one wavelength and re-emit it at a different wavelength, changing its emitting color. The proposed device may rely on engineering the resonant modes of photonic cavities. Specifically, the proposed device may utilize resonant modes of all-dielectric lossless nanoantennas (e.g. subwavelength nanoparticles or nanostructures) and their collective responses when structured in an ordered periodic array. By carefully controlling geometric parameters of nanoantennas, cavity modes of different natures may be tailored to match the absorption spectra of the active material (e.g. active or gain medium). This may ensure maximum overlap and energy transfer between the cavity mode and the active material

leading to enhancing the absorption of incident light and consequently the color-conversion efficiency.

[00023] In some embodiments, the proposed device for color conversion may include a planar photonic cavity made of pillar-like nanoantennas and complemented on one side by a Distributed Bragg Reflector (DBR). The present disclosure offers a novel approach to enhancing photon absorption, achieving a multifold improvement compared to conventional slab cavities. The proposed device may absorb light from a wide range of angles and arbitrary polarizations, a characteristic that aligns with the isotropic light emission typically seen in established LED sources. Notably, the proposed device may allow for the seamless integration of sensitive emitters at the final stage, minimizing fabrication-induced degradation and further elevating overall color conversion efficiency. The proposed device may employ a DBR configuration to effectively manage incident light, enabling nearly unperturbed high-purity transmission of the converted light. Additionally, by reducing the structure thickness for efficient light absorption afforded by an optimized photonic cavity, the proposed device may naturally reduce or prevent waveguided light within the gain medium leading to enhanced light extraction efficiency. With its versatile applications spanning LEDs, detectors, and beyond, this present disclosure paves the way for advanced optoelectronic devices.

[00024] Various embodiments of the present disclosure seek to provide a device for color conversion. The proposed device may include a substrate; a distributed Bragg reflector (DBR) disposed on the substrate; a metasurface including a plurality of nanostructures extending from the DBR; and an active or gain medium disposed in between the plurality of nanostructures. The plurality of nanostructures may include a first dielectric layer with a first refractive index and a second dielectric layer with a second refractive index, the first refractive index being different from the second refractive index. In some embodiments, the DBR may include alternating layers that have different refractive index(es) (e.g. silicon nitride/silicon dioxide) from the first refractive index and the second refractive index. In other embodiments, the DBR may include alternating layers having the first refractive index and the second refractive index. In other words, the DBR may be made of the same two materials as the first dielectric layer and the second dielectric layer. Furthermore, the surface layer (e.g. a side layer) of the DBR structure may be composed of the same material as the second dielectric layer. Stated differently, at the interface, the DBR and the plurality of nanostructures may be composed of the same material, ensuring continuity in composition and minimizing any refractive index mismatch or structural discontinuities. The plurality of two-layer nanostructures may advantageously provide a denser interface by the second dielectric layer with a higher refractive

index (facing the incident light) and a matching interface by the first dielectric layer with a same refractive index as the surface layer of the DBR. In some embodiments, the active medium may be composed of a material having a similar refractive index as the first refractive index of the first dielectric layer, allowing for longer propagation lengths and accommodating a wider range of incident angles. In other words, it may be preferable that these two materials (i.e. the active medium and the first dielectric layer) support the minimum possible refractive index contrast, with the QDs index remaining denser (i.e. the first dielectric layer having a refractive index higher than a refractive index of the active medium). For example, the active medium may have a refractive index of 1.45 (e.g. SiO₂), which is the closest to the typical QDs index, hovering around 1.8 (e.g. the first dielectric layer of TiO₂).

[00025] The DBR may be optimized to provide a maximally flat response (e.g. a consistent, unaltered reflection across a specified range of wavelengths or frequencies) and a sharp cut-off between the blue and green spectrum, while handling angular dispersions and unpolarized wavefronts. A figure-of-merit algorithm may be utilized (e.g. to minimize average reflection and/or maximize absorption of the DBR) to obtain optimized thickness of the alternating layers, the number of pairs of the alternating layers and/or the materials of the alternating layers (e.g. the refractive indexes (or relating permittivity)).

[00026] The metasurface may be also optimized by using a figure-of-merit algorithm (e.g. to maximize absorption of the metasurface) to obtain optimized size of the plurality of nanostructures including heights and lateral dimensions of the nanostructures, spacings of the plurality of nanostructures, shapes of the plurality of nanostructures, and/or materials of the plurality of nanostructures (e.g. the refractive indexes (or relating permittivity)). Rigorous Coupled Wave Analysis (RCWA) and Particle Swarm Optimization (PSO) may be utilized to simulate the optical response of the metasurface so as to optimize the figure-of-merit algorithm. Local Density of States may be used for selecting the exciting modes with specific quality factors and mode volumes in the optical responses of the metasurface.

[00027] The following examples pertain to various aspects of the present disclosure.

[00028] Example 1 is a device for color conversion including: a substrate; and a plurality of nanostructures disposed over the substrate, wherein the plurality of nanostructures includes a first dielectric layer with a first refractive index and a second dielectric layer with a second refractive index, the first refractive index being different from the second refractive index.

[00029] In Example 2, the subject matter of Example 1 may optionally include that the first refractive index is larger than the second refractive index.

[00030] In Example 3, the subject matter of Example 1 or 2 may optionally include that a first height of the first dielectric layer is less than or greater than a second height of the second dielectric layer.

[00031] In Example 4, the subject matter of any of Examples 1 to 3 may optionally include an active or gain medium, wherein the active or gain medium is disposed in between the plurality of nanostructures.

[00032] In Example 5, the subject matter of Example 4 may optionally include that the active or gain medium includes a gain refractive index less than the first refractive index.

[00033] In Example 6, the subject matter of any of Examples 1 to 5 may optionally include a photonic filter layer disposed on the substrate, wherein the plurality of nanostructures extends from on a first side of the photonic filter layer, and wherein the photonic filter layer includes a distributed Bragg reflector (DBR).

[00034] In Example 7, the subject matter of Example 6 may optionally include that the DBR includes alternating dielectric layers having the first refractive index and the second refractive index.

[00035] In Example 8, the subject matter of Example 6 or 7 may optionally include a glass layer extending from a second side of the photonic filter layer, wherein the second side of the photonic filter layer being opposite to the first side of the photonic filter layer.

[00036] In Example 9, the subject matter of any of Examples 6 to 8 may optionally include that the DBR includes silicon dioxide (SiO₂)/ titanium dioxide (TiO₂) alternating layers.

[00037] In Example 10, the subject matter of any of Examples 1 to 9 may optionally include that a difference between a center-to-center distance of adjacent nanostructures of the plurality of nanostructures and a sum of cross-section dimensions of the adjacent nanostructures of the plurality of nanostructures is equal to or larger than a minimum feature size threshold.

[00038] In Example 11, the subject matter of any of Examples 1 to 10 may optionally include that the plurality of nanostructures includes a same cross-section dimension or a varying cross-section dimension.

[00039] In Example 12, the subject matter of any of Examples 1 to 11 may optionally include that a cross-section dimension of the plurality of nanostructures is determined by Particle Swarm Optimization method, Rigorous Coupled Wave Analysis and/or Local Density of States.

[00040] In Example 13, the subject matter of any of Examples 1 to 12 may optionally include that a periodicity of the plurality of nanostructures is less than or comparable to a wavelength of incident light.

[00041] Example 14 is a method for forming a device for color conversion, the method including: forming a second dielectric layer with a second refractive index over a substrate; forming a first dielectric layer with a first refractive index on the second dielectric layer; forming a plurality of nanostructures based on the second dielectric layer and the first dielectric layer using photolithography, wherein the first refractive index is different from the second refractive index.

[00042] In Example 15, the subject matter of Example 14 may optionally include that the first refractive index is larger than the second refractive index.

[00043] In Example 16, the subject matter of Example 14 or 15 may optionally include that a first height of the first dielectric layer is less than or greater than a second height of the second dielectric layer.

[00044] In Example 17, the subject matter of any of Examples 14 to 16 may optionally include forming an active or gain medium in between the plurality of nanostructures.

[00045] In Example 18, the subject matter of Example 17 may optionally include that the active or gain medium includes a gain refractive index comparable to or less than the first refractive index.

[00046] In Example 19, the subject matter of any of Examples 14 to 18 may optionally include that prior to forming a second dielectric layer with a second refractive index over a substrate, further including: forming a photonic filter layer on the substrate; and forming the second dielectric layer with the second refractive index on the photonic filter layer, wherein the photonic filter layer includes a distributed Bragg reflector (DBR).

[00047] In Example 20, the subject matter of Example 19 may optionally include that the DBR includes alternating dielectric layers having the first refractive index and the second refractive index.

[00048] Due to the relatively small absorption cross-section, particularly noticeable with green quantum dots (QDs), a thick layer of these QDs, reaching tens of microns, becomes necessary to fully absorb the blue light emitted by microLEDs. This challenge intensifies as pixels are reduced to a few microns in high-resolution displays. One way to address these hurdles is to use resonant nanostructures, so-called nanoantennas, that can enhance QD layer absorption while controlling its emission directionality. Resonant nanostructures may be employed to amplify emitter fluorescence through the Purcell effect. However, these structures usually possess a limited mode volume, enabling only a fraction of QDs within specific "hotspots" to couple with the mode and be boosted. This limitation hampers their application

to the color conversion process within microLED displays, where a substantial amount of QDs is essential to completely absorb the blue light.

[00049] Another widely utilized approach relies on the Fabry-Perot (FP) cavities. By sandwiching the QD layer between two distributed Bragg reflectors (DBR) mirrors, which guide the blue light within the layer, QD absorption can be significantly increased, thereby enhancing color conversion efficiency. However, the fabrication of DBR top mirrors necessitates vacuum deposition techniques like sputtering or thermal evaporation. Unfortunately, this process often results in damage to the QD layer situated beneath the mirror. Additionally, DBRs require a uniform QD thickness across the pixel and a smooth optical surface, aspects that are frequently challenging to achieve using solution-based patterning methods. Furthermore, conventional QD-based micro-LED displays commonly encounter issues related to trapped light between the encapsulation and QD layers due to total internal reflection which leads to reduced light extraction efficiency and increased losses due to side-wall absorptions.

[00050] Hence, the pressing need emerges for a resonant structure that offers a larger mode volume while allowing relaxed conditions for QDs integration. This structure would be a game-changer in color conversion technology, resolving critical issues in microLED displays and paving the way for efficient and vibrant visual displays.

[00051] For the purpose of increasing energy transfer to the QD medium, there have been several works that investigated ways to bring the source LEDs in a direct contact with the QDs. This can be achieved by designing the source LEDs as a photonics slab with holes filled by QDs. In addition to the radiative transfer, the energy transfer process can be nonradiative this way, a so-called Förster resonance energy transfer (FRET). When the QDs are close to the LED active region, electrons can directly be transferred to QDs without going through the two-step process of short-wavelength photon generation and electron excitation in the QDs. As a result, the color-conversion quantum yield of a single QD (monochromatic conversion) was noticeably enhanced. At the same time, the photonic crystal structure enables access to guided modes and better extracting the generated light. Despite the promising results of this technology, there are several disadvantages. Mainly it is highly risking the degradation of the LED source by etching its active medium, it reduces the overall efficiency of the LED source by reducing its surface area, and limits the scalability of the device for certain applications because of the limitations on the etching process of the LED. Additionally, having two direct and indirect processes of exciting the QDs leads to slow overall frequency response of the device.

[00052] Selective scatters are typically deep subwavelength nanoparticles that are randomly dispersed in the gain medium area. These scatters are designed to exhibit a non-resonance scattering behaviour at the absorption wavelength of the QDs and a strong resonance scattering at the emission wavelengths. The non-resonant nanoparticles will increase pathway and pathlength of the incident light so that it enhances the chance of light being absorbed in the structure. In the emission regime, they act as strong deflectors of emitted light, thus increasing light extraction efficiency. This technology shows promise mostly in generating white light. However, it is highly invasive and can't be scaled or controlled easily.

[00053] The methods discussed earlier for addressing color conversion challenges via absorption enhancement encounter issues related to invasiveness, complexity, or inefficiency. The proposed device, which employs photonic cavity modes and lossless all-dielectric nanoantennas, may circumvent these drawbacks. It may maintain non-invasiveness for both QDs and the LED source, capitalizing on a rich array of high-quality modes that spatially align with the gain medium to significantly amplify absorption rates. The proposed device may efficiently collect and concentrate incident light from wide angles making it compatible with diverse LED sources. Moreover, the proposed device may offer scalability to various QDs' active frequency bandwidths.

[00054] FIG. 1 is a block diagram showing a cross-sectional view (in the x-z plane) of a device 10 according to various embodiments of the present disclosure. The device 10 may include a metasurface and the metasurface may include: a plurality of nanostructures including 100i, 100ii, 100iii, 100iv, ..., 100n, collectively 100. The plurality of nanostructures 100 may include a first dielectric layer including 110i, 110ii, 110iii, 110iv, ..., 110n, collectively 110, with a first refractive index, and a second dielectric layer including 120i, 120ii, 120iii, 120iv, ..., 120n, collectively 120, with a second refractive index. The nanostructures 100i, 100ii, 100iii, 100iv, ..., 100n of the plurality of nanostructures 100 may each include a first dielectric layer 110i, 110ii, 110iii, 110iv, ..., 110n, respectively, and a second dielectric layer 120i, 120ii, 120iii, 120iv, ..., 120n, respectively, wherein n is an integer. The plurality of nanostructures 100 may have an unvaried height (e.g. thickness) in the vertical dimension (i.e. the z direction), that is, the total height of a first height of the first dielectric layer and a second height of the second dielectric layer. In some embodiments, the first height of the first dielectric layer may be less than or greater than the second height of the second dielectric layer. The plurality of nanostructures 100 may be deposited over a substrate (e.g. directly on the substrate 150 as shown in FIG. 1 or separated by an intermediate layer).

[00055] According to various non-limiting embodiments of the present disclosure, the first dielectric layer 110 and/or the second dielectric layer 120 may be made of Silicon dioxide (SiO_2), Titanium dioxide (TiO_2) or any other transparent dielectric materials (e.g. glass, quartz, sapphire and polymer films). The transparent dielectric materials may allow light to pass through them while exhibiting minimal absorption or scattering. The first refractive index may be different from the second refractive index. In some embodiments, the first refractive index may be larger than the second refractive index. In an example, the first dielectric layer 110 may be made of TiO_2 and the second dielectric layer 120 may be made of SiO_2 .

[00056] According to various non-limiting embodiments of the present disclosure, a cross-section dimension (e.g. a radius or diameter for a circular nanostructure, a width or length for a square nanostructure, etc.) of the plurality of nanostructures 100 may be subwavelength of incident light. A periodicity of the plurality of nanostructures may be less than or comparable to a wavelength of incident light. This may enable the precise engineering of light concentration and localization within specific spatial dimensions, allowing for tailored manipulation of light in ways that enhance performance in various applications.

[00057] According to various non-limiting embodiments of the present disclosure, the device 10 may further include: an active or gain medium (not shown in FIG. 1), wherein the active or gain medium is disposed in between the plurality of nanostructures 100. In other words, the active or gain medium may fill the gaps (e.g. spacings) between the plurality of nanostructures 100. In some embodiments, the active or gain medium may also be disposed on top of the plurality of nanostructures 100.

[00058] As used herein, the term “active medium”, also known as a gain medium, may refer to a material used in optical devices that facilitates the amplification of light through the process of stimulated emission. When energy is supplied to the medium, typically in the form of electrical current or light, it excites atoms or molecules to higher energy levels. As these excited particles return to their lower energy states, they emit photons, and if these photons stimulate other excited atoms to emit more photons in phase, it leads to light amplification. The choice of the gain medium depends on the specific application, with each type offering unique advantages in terms of power, efficiency, and wavelength range for lasers and optical systems. Examples of active medium may include colloidal II–VI quantum dots, such as CdSe/CdS core–shell structures, Perovskite quantum dots, and Cadmium-free InP-based quantum dots. . The device 10 may include the active or gain medium with a low extinction coefficient, similar to a characteristic of quantum dots, for example, green-emitting QDs may possess an imaginary

index as small as $k \sim 0.007$ or lower at the wavelength of blue LED. The active or gain medium may have a gain refractive index comparable to or less than the first refractive index.

[00059] According to various non-limiting embodiments of the present disclosure, the device 10 including the metasurface may include all-dielectric material (e.g. the first dielectric layer 110, the second dielectric layer 120 and an active or gain dielectric medium). The photonic cavity formed by the metasurface and the active or gain medium in device 10, (e.g. an all-dielectric cavity) may provide several key advantages, most notably their low loss and the ability to control the mode volume—the spatial extent of light within the cavity. This level of control is particularly important for optimizing the interaction between light and the material, making it highly relevant for the intended purpose of the technology. By fine-tuning the mode volume, it may become possible to enhance light-matter interactions, improve efficiency, and achieve more precise control over optical processes, which is crucial for a wide range of advanced applications. The proposed device 10 may effectively enhance the absorption rate, promoting higher color conversion efficiencies while minimizing the overall cavity thickness. In contrast to conventional cavities and Distributed Bragg Reflectors (DBR)/slab (DBR/slab) cavities, the proposed device 10 may reduce re-absorption processes within the gain medium, improving the performance and color conversion efficiency of the device. Moreover, the proposed metasurface-assisted cavity may be non-invasive to the delicate gain medium during fabrication, ensuring that the material remains intact. Additionally, the proposed device may incorporate DBR to maintain the purity of the emitted light, as will be explained in further details. The proposed device 10 may open up possibilities for real-world applications, as it is scalable. The operating wavelength of the device 10 may be substantially controlled by meticulously manipulating its geometric degrees of freedom. Potential applications in various display technologies may include vibrant LEDs, AR, and VR, as well as its utilization as a photon detector, capitalizing on the optimized color conversion mechanism.

[00060] FIGS. 2A and 2B show exemplary examples of the device 10 according to various embodiments of the present disclosure. FIG. 2A shows a top view (in the x-y plane) of exemplary supercells 21, 22, 23, of the plurality nanostructures 100 of device 10; and FIG. 2B shows a top view (in the x-y plane) of exemplary nanostructures 24, 25, 26, of the plurality nanostructures 100 of device 10. The plurality nanostructures 100 of device 10 may include multiple periodic supercells with each supercell composed of multiple nanostructures. The multiple nanostructures may be arranged in a specific pattern (as shown in FIG. 2A) within each supercell and the supercells may be arranged periodically, forming a structure of these

repeating specific patterns. The supercell may have wavelength-scale domains of lateral dimensions. Each domain may be subdivided into N nanostructures along the x -axis and M nanostructures along the y -axis such that $\sum_{i=1}^N w_x^i = L_x$ and $\sum_{i=1}^M w_y^i = L_y$, where w_x^i and w_y^i are the nanostructure widths (see the labelled nanostructure in the exemplary example 21). The nanostructures may have either random dimensions or follow specific patterned, utilizing standard or non-standard configurations, such as rectangular, hexagonal, face-centered, and edge-extended layouts, with exemplary nanostructures 24, 25, 26 shown in FIG. 2B. The plurality of nanostructures or a supercell may include a same cross-section dimension or a varying cross-section dimension. A cross-section dimension of the plurality of nanostructures may be determined by Particle Swarm Optimization method, Rigorous Coupled Wave Analysis and/or Local Density of States as described hereinafter. Each nanostructure may be also referred to as a “nanoantenna”.

[00061] According to various non-limiting embodiments of the present disclosure, a single microLED may be composed of one or more supercells (e.g. supercells 21, 22, 23) to form a pixel element. For a smaller microLED pixel—such as those below $5\ \mu\text{m}$ (e.g. $3\ \mu\text{m}$)—a single supercell may suffice. Once the required number of supercells is determined, the lateral dimensions (L_x and L_y) of the supercell may be chosen to cover the pixel’s lateral dimensions. The array constants (w_x and w_y) may then be reoptimized to maximize the figure of merit (fom as defined by Eq. (5)) for each pixel size. Consequently, the number of nanoantennas may scale as

- (number of supercells) $\times (L_x/w_x)$ in the x direction; and
- (number of supercells) $\times (L_y/w_y)$ in the y direction.

Reducing the pixel dimensions—whether for high-resolution display applications, accurate spatial sensing, or other uses—may further challenge the color conversion processes, as the gain medium is confined to smaller microcavity domains. In these embodiments, enhancing the so-called cavity effect may become crucial. For finite arrays, the MDBR structure (e.g. MDBR 50 as described herein) may function as a microcavity, where the optimized resonant modes of an infinite metasurface gradually converge toward the pixel boundaries. This convergence rate may strongly depend on the size of the supercell and the number of nanoantennas it contains.

[00062] According to various non-limiting embodiments of the present disclosure, a difference between a center-to-center distance of adjacent nanostructures of the plurality of nanostructures and a sum of cross-section dimensions of the adjacent nanostructures of the

plurality of nanostructures may be equal to or larger than a minimum feature size (MFS) threshold, to satisfy certain experimental feasibility conditions (e.g. achievable by the fabrication method). For instance, an MFS for two neighboring circular nanoantennas may be set as:

$$p - (r_1 + r_2) \geq MFS \quad (1)$$

where r_1 and r_2 are the radii of the nanoantennas, and p is the centre-to-centre distance of adjacent nanoantennas. In an example, the MFS may be greater than 30 nm, as the typical etching limitations for the state of the art electron beam and photolithography machines.

[00063] FIG. 3A is a block diagram showing a cross-sectional view (in the x-z plane) of a device 30 according to various embodiments of the present disclosure. The device 30 may include similar features of the device 10 as described above in connection to FIG. 1, and therefore, features that are described in the context of the device 10 may correspondingly be applicable to the same or similar features in the device 30 and *vice versa*. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of the device 10 may correspondingly be applicable to the same or similar feature in the device 30 and *vice versa*.

[00064] The device 30 may include a metasurface and the metasurface may include: a plurality of nanostructures including 100i, 100ii, 100iii, 100iv, ..., 100n, collectively 100. The plurality of nanostructures 100 may include a first dielectric layer including 110i, 110ii, 110iii, 110iv, ..., 110n, collectively 110, with a first refractive index, and a second dielectric layer including 120i, 120ii, 120iii, 120iv, ..., 120n, collectively 120, with a second refractive index. These reference numerals for each nanostructure are not shown in FIG. 3A to avoid cluttering. The first dielectric layer may face the incoming light λ_{in} . The first refractive index may be different (e.g. distinct) from the second refractive index. In some embodiments, the permittivity ϵ_1 (e.g. relating to the first refractive index) of the first dielectric layer as in shown in the inset 33 of FIG. 3A may be larger than the permittivity ϵ_2 (e.g. relating to the second refractive index) of the second dielectric layer as shown in the inset 32 of FIG. 3A. In some embodiments, a first height h_1 of the first dielectric layer 110 may be less than or greater than a second height h_2 of the second dielectric layer 120, as labelled in FIG. 3A.

[00065] According to various non-limiting embodiments of the present disclosure, the device 30 may include: an active or gain medium 330, wherein the active or gain medium 330 is disposed in between and on the plurality of nanostructures 100. The active or gain medium 330 may have a gain refractive index (a relating permittivity ϵ_a) comparable to or less than the

first refractive index. The gain medium 330 confined around the plurality of nanoantennas 100 may effectively trap and increase the optical propagation length of the incoming light, accommodating wide incident angles and maximizing absorption of incoming light inside the gain medium 330.

[00066] According to various non-limiting embodiments of the present disclosure, the device 30 may further include a photonic filter layer disposed on a substrate, wherein the plurality of nanostructures 100 extends from on a first side of the photonic filter layer, and wherein the photonic filter layer includes a distributed Bragg reflector (DBR) 340. The DBR 340 may be so designed to reflect the incoming light with wavelength λ_{in} and allow for transmission of the color-converted light with wavelength λ_{out} . The DBR 340 may include alternating dielectric layers having the first refractive index and the second refractive index. In other words, the alternating dielectric layers of the DBR 340 may have the same refractive indexes as the first and second dielectric layers of the plurality of nanostructures 100. In some embodiments, the DBR 340 may include silicon dioxide (SiO_2) / titanium dioxide (TiO_2) alternating layers. In some embodiments, a first side layer 341 of the DBR 340 on its first side may have the same refractive index as the second dielectric layer of the plurality of nanostructures 100. Stated differently, the first side layer 341 of the DBR 340 are made of a same material as the second dielectric layer of the plurality of nanostructures 100. It should be appreciated that although FIG. 3A shows the DBR 340 includes two pairs of alternating layers, the DBR 340 may include any pairs of alternating layers, three pairs or more.

[00067] According to various non-limiting embodiments of the present disclosure, the device 30 may further include a glass layer 350 (e.g. a substrate) extending from a second side of the photonic filter layer, wherein the second side of the photonic filter layer being opposite to the first side of the photonic filter layer.

[00068] According to various non-limiting embodiments of the present disclosure, incoming light with a wavelength λ_{in} may be trapped and absorbed inside the color conversion cavity 31 (e.g. including the metasurface-assisted active medium 330 and the DBR 340). The gain medium 330 within the cavity 31 may convert the absorbed light to light with a different (e.g. longer) wavelength λ_{out} . The converted light may be emitted through the glass layer (e.g. the substrate) 350.

[00069] FIG. 3B is a block diagram showing a cross-sectional view (in the x-z plane) of another device 35 according to various embodiments of the present disclosure. The device 35 may include similar features of the device 30 as described above in connection to FIG. 3A, and therefore, features that are described in the context of the device 30 may correspondingly be

applicable to the same or similar features in the device 35 and vice versa. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of the device 30 may correspondingly be applicable to the same or similar feature in the device 35 and vice versa.

[00070] Similarly, the device 35 may include a metasurface and the metasurface may include: a plurality of nanostructures including 100i, 100ii, 100iii, 100iv, ..., 100n, collectively 100. The plurality of nanostructures 100 may include a first dielectric layer including 110i, 110ii, 110iii, 110iv, ..., 110n, collectively 110, with a first refractive index, and a second dielectric layer including 120i, 120ii, 120iii, 120iv, ..., 120n, collectively 120, with a second refractive index. These reference numerals for each nanostructure are not shown in FIG. 3B to avoid cluttering. The first dielectric layer may face the incoming light λ_{in} . The first refractive index may be different (e.g. distinct) from the second refractive index. In some embodiments, the permittivity ϵ_1 (e.g. relating to the first refractive index) of the first dielectric layer as in shown in the inset 38 of FIG. 3B may be larger than the permittivity ϵ_2 (e.g. relating to the second refractive index) of the second dielectric layer as shown in the inset 37 of FIG. 3B. In some embodiments, a first height h_1 of the first dielectric layer 110 may be less than or greater than a second height h_2 of the second dielectric layer 120, as labelled in FIG. 3B.

[00071] According to various non-limiting embodiments of the present disclosure, the device 35 may include: an active or gain medium 330, wherein the active or gain medium 330 is only disposed in between the plurality of nanostructures 100. The active or gain medium 360 may have a gain refractive index (a relating permittivity ϵ_a) comparable to or less than the first refractive index. The gain medium 360 may only confine around the second dielectric layer (with the height of h_2) of the plurality of nanoantennas 100.

[00072] According to various non-limiting embodiments of the present disclosure, the device 35 may further include a photonic filter layer disposed on a substrate, wherein the plurality of nanostructures 100 extends from on a first side of the photonic filter layer, and wherein the photonic filter layer includes a distributed Bragg reflector (DBR) 340. The DBR 340 may be so designed to reflect the incoming light with wavelength λ_{in} and allow for transmission of the color-converted light with wavelength λ_{out} . The DBR 340 may include alternating dielectric layers having the first refractive index and the second refractive index. In other words, the alternating dielectric layers of the DBR 340 may have the same refractive indexes as the first and second dielectric layers of the plurality of nanostructures 100. In some embodiments, the DBR 340 may include silicon dioxide (SiO_2) / titanium dioxide (TiO_2)

alternating layers. In some embodiments, a first side layer 341 of the DBR 340 on its first side may have the same refractive index as the second dielectric layer of the plurality of nanostructures 100. Stated differently, the first side layer 341 of the DBR 340 are made of a same material as the second dielectric layer of the plurality of nanostructures 100. It should be appreciated that although FIG. 3B shows the DBR 340 includes two pairs of alternating layers, the DBR 340 may include any pairs of alternating layers, three pairs or more.

[00073] According to various non-limiting embodiments of the present disclosure, the device 35 may further include a glass layer 350 (e.g. a substrate) extending from a second side of the photonic filter layer, wherein the second side of the photonic filter layer being opposite to the first side of the photonic filter layer.

[00074] According to various non-limiting embodiments of the present disclosure, incoming light with a wavelength λ_{in} may be trapped and absorbed inside the color conversion cavity 36 (e.g. including the metasurface-assisted active medium 360 and the DBR 340). The gain medium 360 within the cavity 36 may convert the absorbed light to light with a different (e.g. longer) wavelength λ_{out} . The converted light may be emitted through the glass layer (e.g. the substrate) 350.

[00075] The device 35 may include the identical MDBR structure (i.e. the DBR 340 and the metasurface 100) as the device 30, with the exception that the QDs coating level (i.e. the gain medium 360) is controlled and lowered to uncover the first dielectric layer (e.g. TiO_2 layer) of the plurality nanostructures (nanoantennas) 100 to the free space (air) as the superstrate. The geometric parameters of the nanoantennas and the corresponding metasurface array may be reoptimized to achieve *fom* maxima, as outlined in Eq. (5). Exposing the first dielectric (e.g. TiO_2) nanoantennas to free space may achieve an important goal, as the index contrast in the metasurface domain is now larger. This may enable more defined resonant modes of the structure, which may be utilized to in-couple the pumped light into the cavity.

[00076] The optical response of the color conversion cavity 31, 36 may be comprehended using the standard Gires-Tournois etalon, also known as the asymmetric Fabry-Perot etalon. The Gires-Tournois etalon may consist of a transparent plate with two reflecting surfaces (e.g. two mirrors). One surface has very high reflectivity, ideally unity, while the other is partially reflective. The Gires-Tournois etalon may function as a standing-wave optical cavity, reflecting light across all relevant wavelengths while exhibiting pronounced phase delay dispersion. By controlling the phase delay at the resonance wavelength for specific angles of incidence, optimal power transfer to the optical cavity may be achieved. This enhanced power transfer,

akin to resonance critical coupling, may be analogous to maximizing absorption in the presence of materials with minimal Joule losses.

[00077] The conditions for maximized absorption in such asymmetric Fabry-Perot structures made of two mirrors may be set as:

$$|r_{12}| = |r_{23}|e^{-\alpha h} \quad (2)$$

$$\varphi_{23} + 2\varphi_p + \varphi_{21} = 2m\pi \quad (3)$$

where $r_{ij} = |r_{ij}|e^{i\varphi_{ij}}$ are the complex Fresnel reflection coefficients at the interfaces from medium i to medium j , φ_p is the phase accumulated by one round of propagation inside the active medium, h is the thickness of the active medium between the two mirrors, α is the absorption rate in this active medium, and m is an integer. Here, the three media are free space (1st), active medium (2nd) and the substrate (3rd). The condition (eq.(2)) implies a balance of the wave amplitudes reflected at the two interfaces and the amount of power absorbed by the active medium. It is a necessary condition for an interference to occur. A poor top reflector (small r_{12}) then may be compensated either by introducing more losses in the optical cavity (α) or increase the thickness of the said cavity. The second condition (eq. (3)) is exactly the condition for resonances in optical cavities to occur in general. A multiple of (2π) phase may result in a complete destructive interference and formulation of a standing (circling waves) in the optical cavity. Optimizing these two conditions in an experimental setup may be challenging and sometimes impossible due to numerous contributing factors.

[00078] The following will describe the parameter optimization of a DBR structure (e.g. an etalon structure) in the context of color conversion with reference to FIGS. 4A to 4C and FIGS. 5A and 5B, according to various embodiments of the present disclosure. FIG. 4A shows a block diagram showing a perspective view of a DBR structure 40. The DBR structure 40 may include a slab 41 (e.g. a gain medium), a DBR layer 44 and a substrate 43. The DBR structure 40 may be referred as “DBR/slab”. The incident light λ_{in} may be in the UV-blue region of the visible spectrum and the converted light λ_{out} may be in the green region of the visible spectrum. FIG. 4B show the average reflection ($R_{av}=(R_{TE}+R_{TM})/2$) of the DBR structure 40 as a function of the incident angle θ (y-axis) and wavelength λ (x-axis) of incident light. FIG. 4C shows the average absorption ($A_{av}=(A_{TE}+A_{TM})/2$) of the DBR structure covered by the gain medium slab 50 as a function of the incident angle θ (y-axis) and wavelength λ (x-axis) of incident light working in the Gires-Tournois etalon.

[00079] Referring to FIG. 4A, the upper mirror of the DBR structure 40 with respect to the Gires-Tournois etalon is left to be simply the interface between the incident medium (free

space) and the active medium slab 41. The resultant Gires-Tournois etalon has a strong selective reflector and weak interface reflector. The latter negligibly influences the phase dispersions of reflected and transmitted waves. The figure of merit for the DBR structure 40 (fom_{dbr}) is determined as

$$fom_{dbr} = (R_b^{av} + T_g^{av} + T_r^{av})/3 \quad (4)$$

where R_b^{av} is the average reflection of the unpolarized UV-blue light, and T_g^{av} and T_r^{av} are the average transmission of emitted unpolarized green and red lights, respectively. Hence, the DBR structure 40 may also prevent the pumped light from overlapping with the emitted light thus enhancing the emission purity.

[00080] A Lambertian LED source may be applied as the incident light with an angle spread of up to $\pm 60^\circ$ and a 25 nm bandwidth centered around the blue wavelength of 460 nm. The DBR structure 40 may be optimized to provide a maximally flat response (e.g. a consistent, unaltered reflection across a specified range of wavelengths or frequencies) and a sharp cut-off between the blue and green spectrum, while handling angular dispersions and unpolarized wavefronts, as described herein. Firstly, managing angular dispersion may require precise control over fields interferences in the DBR stack layers to maintain consistent performance across different angles. Secondly, ensuring the DBR is polarization-insensitive may be vital, achieved by designing it to support both TE and TM modes, thus maintaining uniform reflectivity regardless of polarization. Lastly, using a trade-off of the refractive index contrast and number of layers implemented in the DBR structure may be essential for achieving a broad stopband and sharp cut-off, allowing for precise filtering at the blue-green boundary while maintaining compact device. A hybrid optimizer is formed by combining a global stochastic method, such as dual annealing, with a local derivative-based search method like gradient ascent. This hybrid approach leverages the broad exploration capabilities of dual annealing to navigate the entire solution space while using gradient ascent to fine-tune the search in promising regions. Consequently, the optimizer robustly seeks the global maximum of the figure of merit described in eq. 4.

[00081] According to various non-limiting embodiments, the DBR layer 44 may be made of SiO_2 and TiO_2 or other materials which exhibit minimal losses within the region of interest thus confining the absorption mechanism primarily to the active medium. The DBR layer 44 may be made of 3-pairs of $\text{SiO}_2/\text{TiO}_2$ layers with optimized thicknesses obtained in connection with eq. (4). For example, the optimized thickness for each SiO_2 and TiO_2 layer is 68.4 nm and 141.5 nm, respectively. In other words, the thickness of the SiO_2 layer is about half the

thickness of the TiO_2 layer. It shall be appreciated that the number of pairs in the DBR layer 44 may be chosen to be more than three to further enhance the intended performance. It shall also be appreciated that the DBR layers may have varying thicknesses, resulting in an aperiodic DBR. The absorption in the etalon structure 40 is examined by introducing small Joule losses $n_g \sim 1.775 + 0.007i$, where n_g is the gain medium refractive index. The average absorption is presented in FIG. 4C showing low on-average absorption rates with maximum below 0.38. The reason for that may be readily understood from the above eqs. (2) and (3). The top interface (i.e. the interface between the incident medium (free space) and the active medium slab) of the DBR structure 40 is optically ineffective such that it imparts approximately zero phases on the reflected waves ($\varphi_{21} \sim 0$) within the cavity. Eq.(3) may be reduced then to read as $\varphi_{23} + 2\varphi_p = 2m\pi$, this implies a multiple of 2π may be accumulated by relatively small thickness of the active medium layer 41 considering the DBR structure 40 may add almost constant phases for various angles of incidence performing as an opaque substrate. However, the low reflection rate of this upper mirror (i.e. the interface between the incident medium (free space) and the active medium slab 41) leads to unsatisfactory conditions described by eq. (2).

[00082] To enhance the absorption of materials with low absorption cross-section, the upper mirror of the DBR structure 40 (i.e. the interface between the incident medium (free space) and the active medium slab) may be modified to enhance its reflection modulation. In principle, this may be achieved by designing a further upper DBR mirror, however, this design may increase the thickness of the color conversion device and complicate its functionality integrations in addition to the drawbacks mentioned in previous section.

[00083] The present device provides a better solution by integrating a metasurface (i.e. as a mirror of the etalon) to the DBR structure 40 to form the DBR structure 50, since it may exhibit multiple resonances that may potentially be employed to enhance the overall absorption rate while occupying relatively small volumes. FIG. 5A shows a block diagram showing a perspective view of the DBR structure 50 integrated with a metasurface 52 (e.g. including a plurality of nanostructures 100) according to various embodiments of the present disclosure. The DBR structure 50 may be referred as “Metasurface-DBR (MDBR)” (e.g. the device 30). The incident light λ_{in} may be in the blue region of the visible spectrum and the converted light λ'_{out} may be in the green region of the visible spectrum. The metasurface 52 (e.g. including the plurality of nanostructures 100) may be designed as periodic tall nanopillars made of, similarly to the DBR layer 41, from SiO_2 and TiO_2 or other transparent dielectric materials (to the

wavelength of choice) with different refractive indices. The average absorption ($A_{av}=(A_{TE}+A_{TM})/2$) of the MDBR structure 50 is shown in FIG. 5B.

[00084] Metasurfaces may inherently possess localized resonances that are highly responsive to the incident light's state. The figure of merit for the metasurface 52, denoted as fom_{abs} , may be set as

$$fom_{abs} = \int u_{norm} A_{av} d\lambda d\theta d\phi \quad (5)$$

herein, u_{norm} represents a multi-dimensional normal distribution characterizing the spectral and angular power distribution of the Lambertian source. It can be defined, for optimization purposes, as the multiplications of three parameters as following $u_{norm} = u(\lambda)u(\theta)u(\phi)$, where $u(\cdot)$ follows a Gaussian distribution for the wavelength (λ), polar angle (θ), and azimuthal angle (ϕ). The term $A_{av} = (A_{TE} + A_{TM})/2$ represents the computed average absorption, considering both transverse electric (A_{TE}) and transverse magnetic (A_{TM}) polarizations for unpolarized incident light. The following will describe the parameter optimization of the metasurface 52. FIG. 5B shows the average absorption ($A_{av}=(A_{TE}+A_{TM})/2$) of the DBR structure 50 including the metasurface 52 as a function of the incident angles (y-axis) and the spectrum of wavelengths (λ) (x-axis) according to various embodiments of the present disclosure.

[00085] To effectively confine maximal energy within the cavity, a brute force simulation methodology may be employed to optimize in accordance with eq. (5). In the case of Lambertian Light Emitting Diodes (LEDs), this simulation may necessitate repetitive execution to account for variations in incident angles, polarizations, and wavelengths. Rigorous Coupled Wave Analysis (RCWA) may be utilized to rigorously compute the structural optical response. In this process, the incident plane wave may be swept across incident angles ranging from 0 to 60 degrees, covering a specified spectral range of 25 nm bandwidth representing the gain medium absorption range centered around the blue color wavelength (460 nm). RCWA allows for simultaneous computation of optical responses for both TE and TM polarization states of the incident light at each angle-wavelength combination. To ensure convergence of RCWA computations its Fourier decomposition order may be set to 50 or higher, which may imply that the solver is precisely resolving the in-plane distribution of the structure permittivity.

[00086] Upon applying the absorption figure of merit (eq. (5)) to the DBR structure 40, it is observed that a maximum absorption fom_{abs} of ~17% can be achieved for the DBR structure 40. The average absorption of FIG. 4C was used for computing the maximum absorption fom_{abs} . In the optimized MDBR configuration 50, the absorption figure of merit (fom_{abs})

demonstrates a noteworthy enhancement, achieving an average of approximately fom_{abs} of 43%. This improvement is particularly significant, as it represents an almost more than twofold increase in absorption efficiency compared to the DBR/slab structure 40. Furthermore, it surpasses the performance of a basic slab structure by several times, which only attains fom_{abs} of 8% for an equivalent cavity thickness.

[00087] The optimization of the metasurface 52 in the MDBR 50 may be done separately after optimizing the DBR response or concurrently by combining the two figures of merits discussed previously. A separate optimization procedure may be considered to reduce the parametric space and computational cost if the modal coupling of the DBR bandgap at the blue region and the metasurface's resonant modes is negligible. In the context of the brute force optimization outlined earlier, the Particle Swarm Optimization method (PSO) together with RCWA may be utilized to track and update a set of geometrical parameters of the metasurface (as shown in FIG. 2A) while improving the absorption figure of merit (fom_{abs}).

[00088] Alternatively, or additionally, the Local Density of States (LDOS) associated with a photonic cavity may offer an alternative method for selecting the exciting modes with specific quality factors and mode volumes. Moreover, LDOS computation is conducted via real-frequency simulations. This characteristic obviates the requirement to calculate the cavity's eigenmodes, a task that can be exceptionally challenging and computationally expensive. The frequency-averaged LDOS is evaluated as follows:

$$\tilde{f}(\omega, J(r)) = -\frac{6}{\pi} R\{J^* \cdot E\} \quad (6)$$

where the current density $J(r) = \delta(r - r_0) \hat{e}_j$ defined at complex frequency $\tilde{\omega} = \omega + i\Gamma$, is used to solve the Maxwell's scattering problem, where r_0 represents the location of the current source within the unit cell or supercell, and $\hat{e}_j$ can be understood as a point dipole polarization in the direction j , with $(j=x, y, z)$. The spatial positioning and polarization of this point current source are judiciously adjusted to selectively excite specific modes. Notably, achieving high-quality modes is attainable by assigning small values to the imaginary part (Γ) of the complex frequency ($\tilde{\omega}$). Furthermore, positioning the point source away from the cell center within the gain medium domain allows for the excitation of modes with the desired eigenfield spread.

[00089] The average absorption of the optimized metasurface 52 which varies with source parameters is visually depicted in FIG. 5. The metasurface 52 may employ a square supercell, featuring circular pillar cross-sections with a 90 nm radius and a lattice constant of 310 nm. In other words, the plurality nanostructures 100 may include a plurality of circular pillars having a radius of 90 nm and a center to center distance or the lattice constant may be 310 nm. The

plurality of nanostructures 100 may have a height of 450 nm. The first dielectric layer of the plurality nanostructures 100 may be made of TiO_2 with a first height of 200 nm and the second dielectric layer of the plurality nanostructures 100 may be made of SiO_2 with a second height of 250 nm. In other words, the cavity may have an overall thickness of 450 nm.

[00090] FIG. 6 shows dispersion bands of the device 30. The shaded regions 61, 62, 63 in various grey shades represent the photonic bands associated with the red, green and blue regions of the visible spectrum, respectively. Four bands as denoted by “a-d” in FIG. 6 exhibit slow dispersion along the G-X direction in the Brillouin zone. The frequency axis is normalized with respect to the lattice constant.

[00091] The presence of four slowly-dispersive bands in the blue region, as denoted by “a-d” in FIG. 6 and corresponding to bands 7-10 in conventional nomenclature (where band 0 is referenced from the lowest frequency point denoting the fundamental band), is preferable. As demonstrated in the x-y plane (FIG. 7) and x-z plane (FIG. 8), these bands exhibit properties encompassing both transverse electric (TE) and transverse magnetic (TM) modes. These bands are classified as TE or TM depending on the dominant proportion of the in-plane electric or magnetic field components, respectively. Bands 'a' and 'b' prominently display dominant E_x components of the electric eigenfields with non-negligible E_y components, associating these two bands with TE_x modes. Conversely, bands 'c' and 'd' exhibit dominant E_z components of the electric eigenfields, associating them with TM_x modes.

[00092] FIG. 7 shows distribution of eigenfields in the central x-y plane of the first/ SiO_2 dielectric layer of the device 30. Each row of bank-specific subplots corresponds to the field components, $|E_x|$, $|E_y|$, and $|E_z|$, respectively.

[00093] FIG. 8 shows distribution of eigenfields in the x-z plane of the device 30, extending to both the second/ SiO_2 (white line) and first/ TiO_2 (white dash-line) dielectric layers. Each row of band-specific subplots corresponds to the field components, $|E_x|$, $|E_y|$, and $|E_z|$, respectively.

[00094] The slow-dispersion and uniform spatial distribution of the eigenfields linked to bands 'a' and 'b' ensure robust overlapping with incoming Lambertian light across a broad range of angles. Furthermore, the eigenfields associated with these four bands exhibit a substantial spatial overlap with the gain medium 330 surrounding the nanoantennas 100 (as seen in FIG. 8). This spatial overlap significantly enhances the power transfer to the gain medium 330, thereby increasing the technology's effectiveness. Furthermore, in the green and red regions, as indicated by the color-coded areas in FIG. 6, a wide band-gap is formed for the guided modes

which are situated below the shaded cone 64. These modes typically contribute to guiding the emitted light within the metasurface domain. However, the reduced overlap of the gain-medium emission with these confined modes ensures enhanced light extraction efficiency.

[00095] FIG. 9 is a flowchart showing a method 900 for forming a device for color conversion according to various embodiments of the present disclosure. According to various non-limiting embodiments, the method 900 may include: at step 902, forming a second dielectric layer with a second refractive index over a substrate; at step 904, forming a first dielectric layer with a first refractive index on the second dielectric layer; at step 906, forming a plurality of nanostructures based on the second dielectric layer and the first dielectric layer using photolithography. The first refractive index may be different from the second refractive index. The first refractive index may be larger than the second refractive index.

[00096] According to various non-limiting embodiments of the present disclosure, the first height of the first dielectric layer may be less than or greater than a second height of the second dielectric layer.

[00097] According to various non-limiting embodiments of the present disclosure, the method 900 may include: forming an active or gain medium in between the plurality of nanostructures. The active or gain medium may include a gain refractive index less than the first refractive index.

[00098] In some embodiments, an excess removal process may be optimized to achieve a controlled level of QD coating (e.g. as described with reference to FIG. 3B). In other words, forming an active or gain medium in between the plurality of nanostructures may include an excess removal process, e.g. to form the device 35. FIG. 10 show an excess removal process 1000, according to various embodiments of the present disclosure.

[00099] FIG. 10 will be described with reference to forming the device 35. At step 1100, a thinner lift-off mask 1001 may be applied solely to the height of the second dielectric (e.g. SiO₂) layer, leaving the first dielectric (e.g. TiO₂) nanoantennas exposed. The thinner lift-off mask 100 may be deposited around the plurality of nanostructures 100, enclosing or bordering them, at a certain time period and to a height same as the height of the second dielectric (e.g. SiO₂) layer. At step 1200, the gain medium (e.g. QDs) 370 may be then spin-coated over the entire surface, depositing the gain medium 370 uniformly and filling the spaces between and on the nanoantennas 100. At step 1300, excess gain medium may be removed using a controlled solvent confined to the thin mask level; the spinning process may prevent the solvent from entering the gaps between the second dielectric (e.g. SiO₂) nanoantennas such that the gain medium deposited between the nanoantennas are remained. Finally, at step 1400, the lift-off

process may remove the mask 1001 and the gain medium on top of it, leaving gain medium 380 only in the regions between the second dielectric (e.g. SiO₂) nanoantennas while keeping the first dielectric (e.g. TiO₂) nanoantennas uncovered.

[000100] According to various non-limiting embodiments of the present disclosure, the method 900 may further include: prior to the steps 902 and 904, forming a photonic filter layer on a glass layer, wherein the photonic filter layer includes a distributed Bragg reflector (DBR). The DBR may include alternating dielectric layers having the first refractive index and the second refractive index.

[000101] The two dielectric layers of plurality of nanostructures may be etched on the DBR before depositing the active medium to avoid degradation of its emission quality. Furthermore, in a particular embodiment presented here, SiO₂ may be used as the second dielectric layer in the plurality of nanostructures since this material and the active medium show similar refractive index, therefore simplifying the optimization of the optical cavity. In other words, this present method may prevent degrading the emissions efficiency from etching and other fabrication processes.

[000102] While the method described above is illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

[000103] While this specification contains many details, these should not be understood as limitations on the scope of what may be claimed, but rather as descriptions of features specific to particular examples. Certain features that are described in this specification or shown in the drawings in the context of separate implementations can also be combined. Conversely, various features that are described or shown in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination.

[000104] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it

should be understood that the described program components and systems can generally be integrated together in a single product or packaged into multiple products.

[000105] A number of implementations have been described. Nevertheless, it will be understood that various modifications can be made. Accordingly, other implementations are within the scope of the following claims.

CLAIMS

1. A device for color conversion comprising:
a substrate; and
a plurality of nanostructures disposed over the substrate,
wherein the plurality of nanostructures comprises a first dielectric layer with a first refractive index and a second dielectric layer with a second refractive index, the first refractive index being different from the second refractive index.
2. The device of claim 1, wherein the first refractive index is larger than the second refractive index.
3. The device of claim 1 or claim 2, wherein a first height of the first dielectric layer is less than or greater than a second height of the second dielectric layer.
4. The device of any of claims 1 to 3, further comprising:
an active or gain medium,
wherein the active or gain medium is disposed in between the plurality of nanostructures.
5. The device of claim 4, wherein the active or gain medium comprises a gain refractive index less than the first refractive index.
6. The device of any of claims 1 to 5, further comprising:
a photonic filter layer disposed on the substrate,
wherein the plurality of nanostructures extends from on a first side of the photonic filter layer, and
wherein the photonic filter layer comprises a distributed Bragg reflector (DBR).
7. The device of claim 6, wherein the DBR comprises alternating dielectric layers having the first refractive index and the second refractive index.
8. The device of claim 6 or claim 7, further comprising:

a glass layer extending from a second side of the photonic filter layer, wherein the second side of the photonic filter layer being opposite to the first side of the photonic filter layer.

9. The device of any of claims 6 to 8, wherein the DBR comprises silicon dioxide (SiO₂)/ titanium dioxide (TiO₂) alternating layers.

10. The device of any of claims 1 to 9, wherein a difference between a center-to-center distance of adjacent nanostructures of the plurality of nanostructures and a sum of cross-section dimensions of the adjacent nanostructures of the plurality of nanostructures is equal to or larger than a minimum feature size threshold.

11. The device of any of claims 1 to 10, wherein the plurality of nanostructures comprises a same cross-section dimension or a varying cross-section dimension.

12. The device of any of claims 1 to 11, wherein a cross-section dimension of the plurality of nanostructures is determined by Particle Swarm Optimization method, Rigorous Coupled Wave Analysis and/or Local Density of States.

13. The device of any of claims 1 to 12, wherein a periodicity of the plurality of nanostructures is less than or comparable to a wavelength of incident light.

14. A method for forming a device for color conversion, the method comprising:
forming a second dielectric layer with a second refractive index over a substrate;
forming a first dielectric layer with a first refractive index on the second dielectric layer;
forming a plurality of nanostructures based on the second dielectric layer and the first dielectric layer using photolithography,
wherein the first refractive index is different from the second refractive index.

15. The method of claim 14, wherein the first refractive index is larger than the second refractive index.

16. The method of claim 14 or claim 15, wherein a first height of the first dielectric layer is less than or greater than a second height of the second dielectric layer.
17. The method of any of claims 14 to 16, further comprising:
forming an active or gain medium in between the plurality of nanostructures.
18. The method of claim 17, wherein the active or gain medium comprises a gain refractive index comparable to or less than the first refractive index.
19. The method of any of claims 14 to 18, prior to forming a second dielectric layer with a second refractive index over a substrate, further comprising:
forming a photonic filter layer on the substrate; and
forming the second dielectric layer with the second refractive index on the photonic filter layer,
wherein the photonic filter layer comprises a distributed Bragg reflector (DBR).
20. The method of claim 19, wherein the DBR comprises alternating dielectric layers having the first refractive index and the second refractive index.