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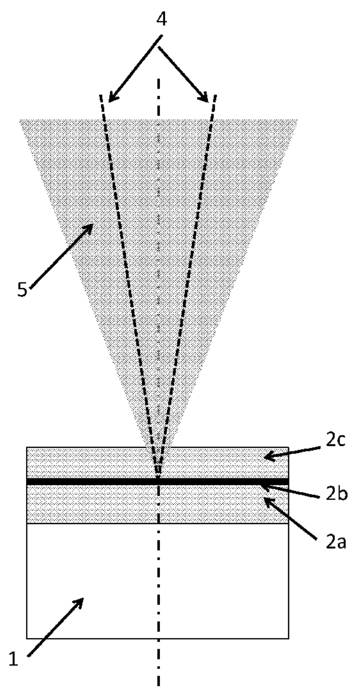
(54) **Title**: HIGHLY DIRECTIONAL LIGHT SOURCE WITH HIGH EXTRACTION EFFICIENCY AND METHOD TO MANUFACTURING THE SAME

Figure 1



(57) **Abstract**: The present invention consists in an LED structure with a narrow angular distribution featuring improved extraction efficiency. The device comprises in particular, but not exclusively an angular bandpass filter reducing the emission angular dispersion, as well as a combination of mirror structure and diffusing elements that redirect the light rejected by the filter within the angular passband, thus improving the extraction efficiency within this passband. Simulations and experiments suggest that in the case of an SiO_2 cavity sandwiched between two DBR mirrors comprising 4 SiO_2/Si_3N_4 pairs each, having a resonance at 430nm, a Lorentzian emission of the light emitters centered in 430nm with a FWHM of 10nm, the angular dispersion is ±16°, and the extraction efficiency is approximately 70%. Introducing a mismatch of 8nm between the LED emission and the cavity mode, the angular dispersion is ±25°, and the extraction efficiency within this cone is close to 90%.

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TITLE: Highly directional light source with high extraction efficiency and method to manufacturing the same

FIELD OF THE INVENTION

The invention relates to LED devices, arrays of LED devices and methods of manufacturing thereof. Specifically, the invention relates to, but is not limited to, LED devices having a plurality of optical components implementable with standard waferscale fabrication techniques. More specifically, the invention relates, but is not limited to, LED devices providing highly directional light output with improved extraction efficiency. The invention can be applied to fields such as, but not limited to, lighting, displays, polymer curing, microelectronic fabrication, telecommunications or biophotonics.

TECHNICAL FIELD

The invention can be incorporate in light projector systems that can be used in fields such as displays, photolithography, 3D printing, biomedical devices, among others.

BACKGROUND

[0001] Many applications require devices having a light beam with an angular dispersion as low as possible.

[0002] Lasers are possible candidates, however coherent light is detrimental to the formation of images, because of the speckling phenomenon. Furthermore, the lasing threshold induces a minimum operating power that is too high for certain applications.

[0003] Light Emitting Diodes (LEDs) are also efficient light sources, emitting non-coherent light, without the inconvenience of laser's threshold, but their angular dispersion is intrinsically very large because of the emission properties of their emitting layers. Standard LEDs have a Lambertian emission. Techniques are currently employed to reduce emission angular distribution. However, most of these techniques are These external elements can be bulky and costly to implement. In addition the apparent source is highly increased when using external optics as the etendue of the system is conserved.

[0004] Resonant Cavity Light Emitting Diode (RCLED) are known to be highly directive, thanks to the use of a resonant cavity. A well-designed cavity allows reducing the number of optical modes that can be outcoupled from the device. Thus, most of the light can be extracted only in specific modes with small angle. The typical divergence half angle of a RCLED can be smaller than 15° while that of a standard LED is usually >60°. However, maximum extraction efficiency of RCLED is theoretically below 30%.

[0005] Other solutions to improve the light emission angular dispersion use substrates with parabolic patterns, described in patent US7518149 B2, or using dual cavity Resonant Cavity LEDs, described in patent DE2000613534. However, these solutions are either hard to implement without affecting the internal quantum efficiency, decreasing the extraction efficiency.

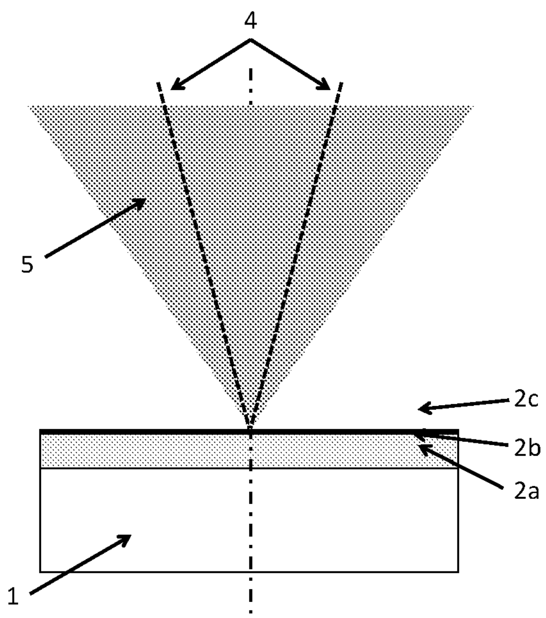
[0006] It is also possible to use external high-performance angular bandpass filters, described in patent US8977082 B2, or implement lenses at packaging level, described in US6547423 B2, even using waferscale compatible process, described in US20140374786 A1. However, these solutions are bulky. In particular, the microoptics are larger than the light emitting part of the devices. This is detrimental to waferscale implementation, where device density needs to be maximized in order to minimize the production cost.

BRIEF SUMMARY OF THE INVENTION

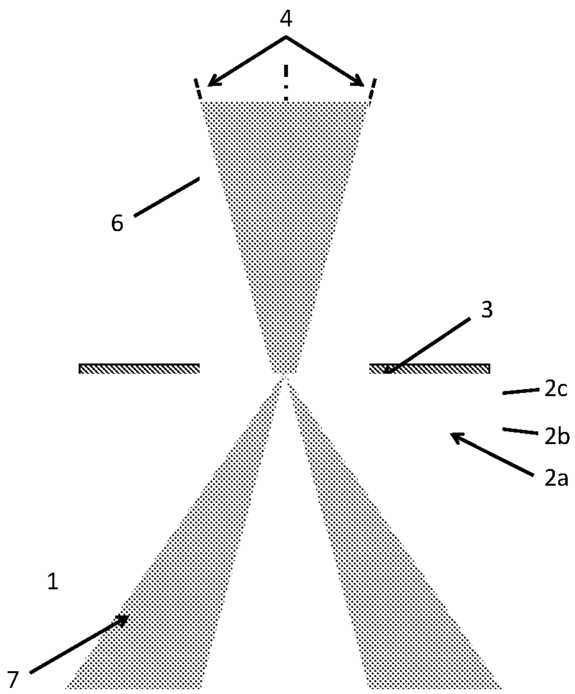
The present invention consists in an LED integrated device. The LED device comprises a semiconductor material comprising a single or a plurality of light generating layers. The light generating layers are positioned below a single or a plurality of layers, structured or not, called the angular filter, which purpose is to let light through within a certain angle, reflecting back the rest of the light. The light generating layers are positioned above a single or a plurality of layers, structured or not, which purpose is to diffuse the light reaching it, called the diffuser, changing the angle with respect to the angular filter. Diffusing layer can have a random pattern providing an isotropic diffusion, or a determined pattern inducing a redirection of light specifically within the angular passband of the angular filter. A mirror layer is placed below the diffuser to reflect back diffused light towards the filter.

BRIEF DESCRIPTION OF THE DRAWINGS

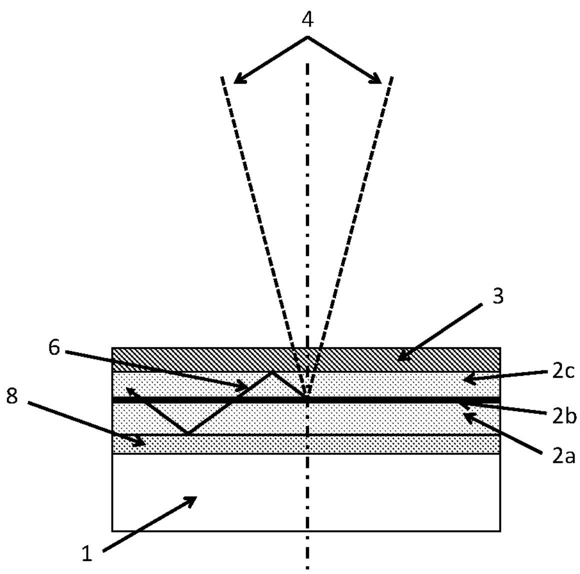
[0008] Figure 1. Figure 1 illustrates the schematics of an LED coupled to a filter that narrows down the emission angular distribution. The substrate (1) serves as basis to the growth of the LED structure consisting in a p-doped contact layer (2a or 2c) and an n-doped contact layer (2c or 2a) respectively, and a part emitting light that can comprise for example, but not exclusively, quantum wells, quantum wires or quantum dots (2b). The emission of the LED outside the device is depicted (5), only limited by total internal reflection. For the sake of comparison, the limits of passband (4) of the angular bandpass filter (3) are depicted in both schematics of figure 1 and 2.



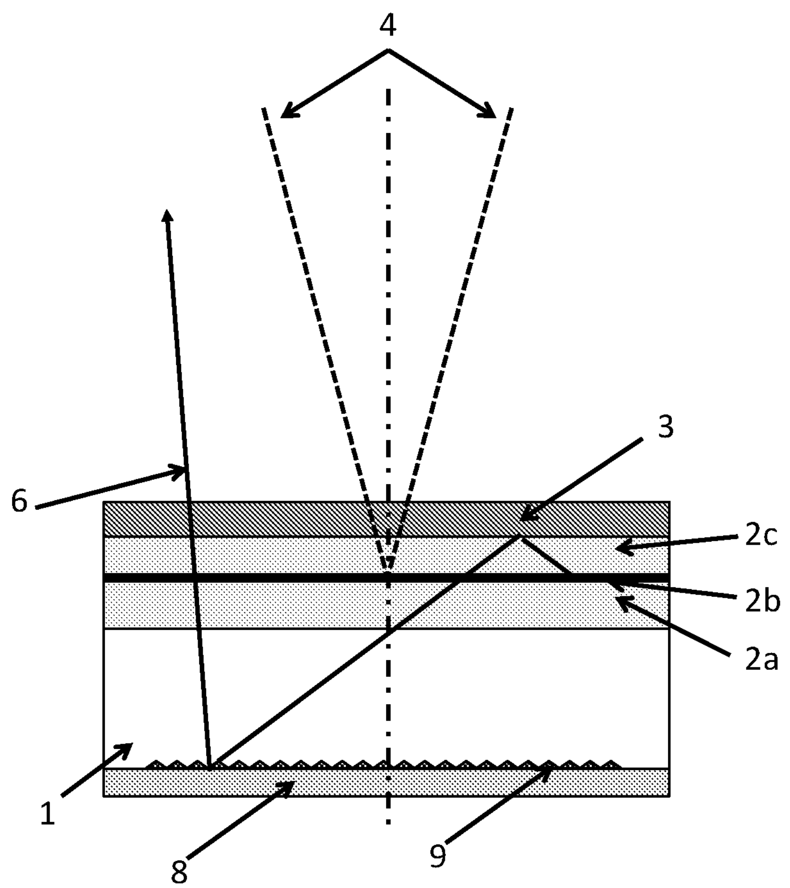
[0009] Figure 2. Figure 2 illustrates the schematics of an LED already presented in figure 1, coupled to a filter that narrows down the emission angular distribution. The actual effect of the angular bandpass filter is an angular selection of the output light beam (6), whereas the part of the light that is not within the angular passband is reflected (7).



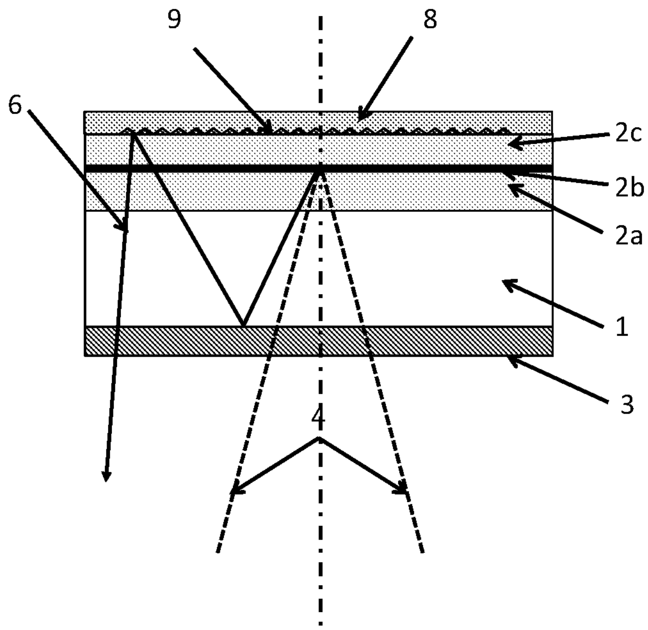
[00010] **Figure 3.** Figure 3 shows the course of a beam of light in a structure prior to art. Photons that are not emitted within the angular bandwidth of the filter are reflected back, decreasing the amount of light in the useful direction. The mirror (8) allows increasing the emission within the angular passband of the filter since it reflects in particular the light that is within the passband of the filter, but directed downward. However, light that is emitted outside the passband of the filter will still remain outside the passband after a reflection on the mirror.



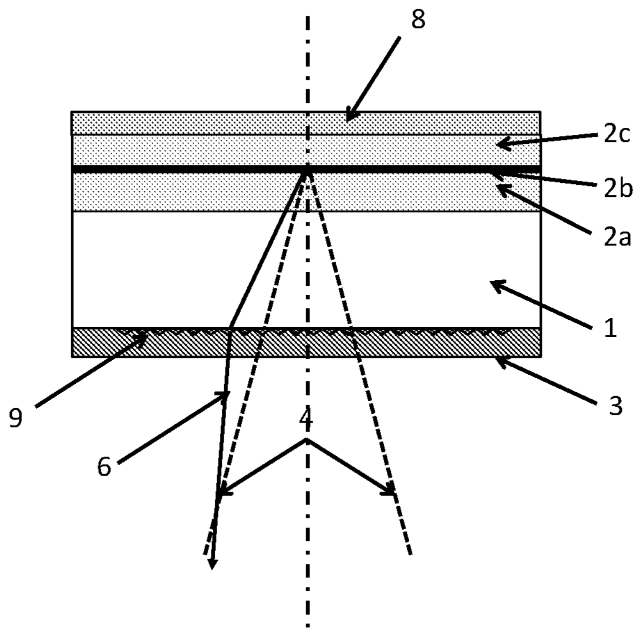
[00011] **Figure 4** shows a possible implementation of the invention that can illustrate its principle. The light rejected by the filter, that is reflected back, is redirected by the diffusing elements, inducing an angle allowing the light to go through the filter. One of these beams is represented (6). The extraction efficiency within the angular passband is therefore increased. Iteratively, in the ideal case where reflectivity of the mirror and that of the filter outside the passband is 1, and the losses within the structure are negligible, all the light produced by the light emitting structure should pass through the filter within its angular passband.



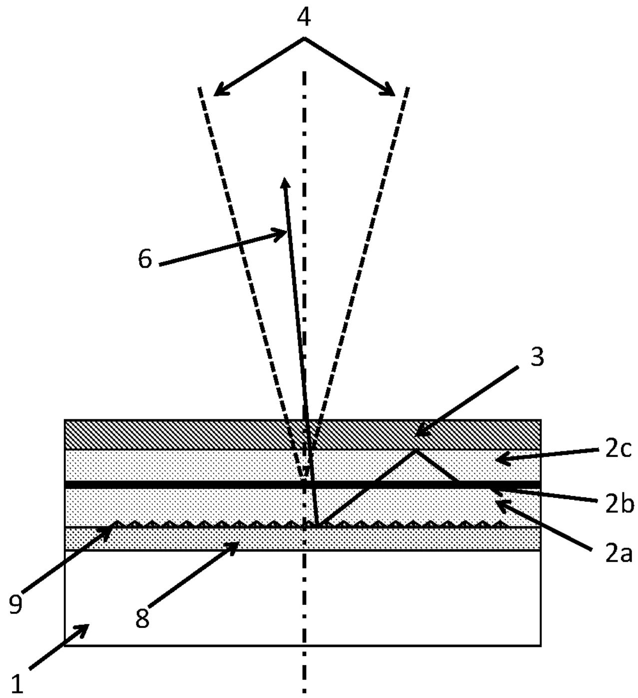
[00012] **Figure 5** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the mirror structure (8) is placed below the substrate (1), the diffusing layer (9) is placed above the emitting structure (2(a), 2(b), 2(c)) and below the angular bandpass filter (3). A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.



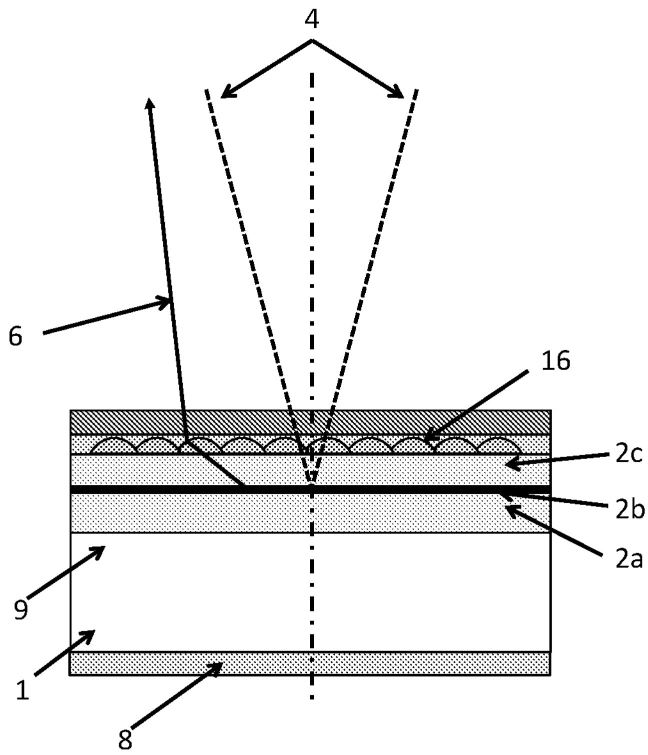
[00013] **Figure 6** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the diffusing layer (9) is placed below the substrate (1), between the substrate and the filter (3) the mirror structure (8) is placed above the emitting structure (2(a), 2(b), 2(c)). A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.



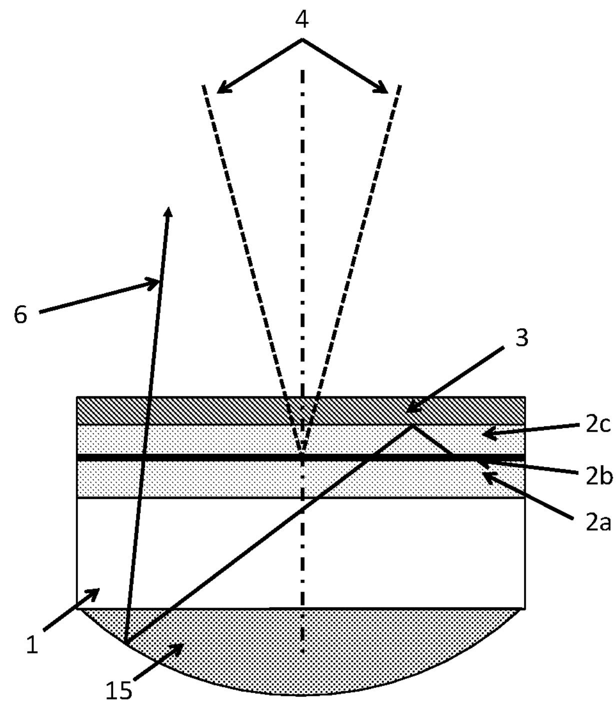
[00014] **Figure 7** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the diffusing layer (9) is placed below the emitting structure (2(a), 2(b), 2(c)) and above the mirror (8), the filter structure (3) is placed above the emitting structure. A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.



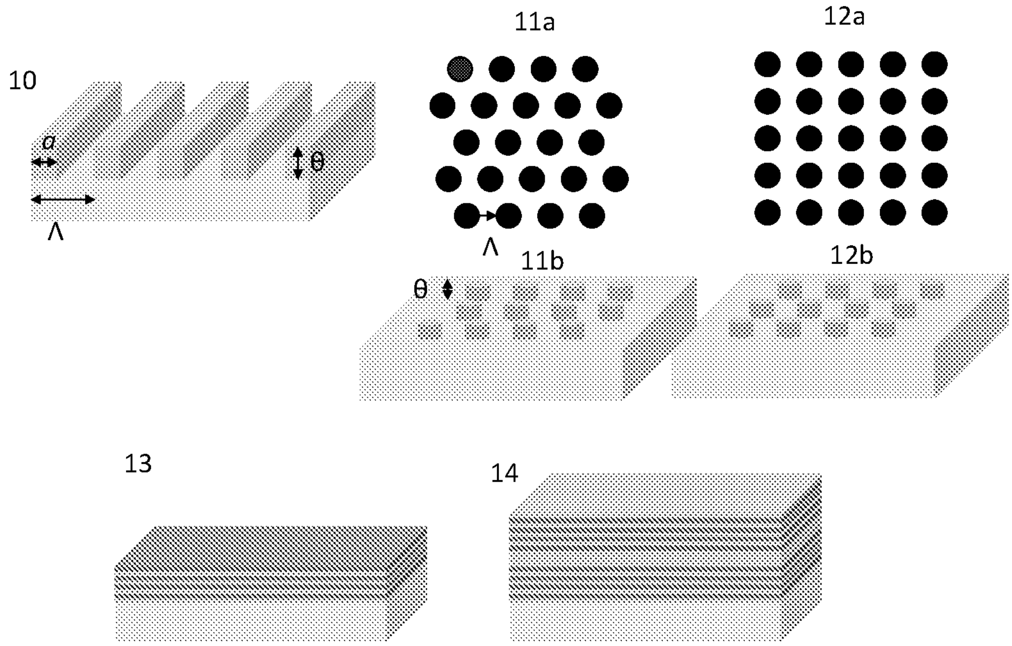
[00015] **Figure 8** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the mirror structure (8) is placed below the substrate (1), the filter (3) is placed above the emitting structure (2(a), 2(b), 2(c)). A layer placed between the emitting structure and the filter comprises focusing or collimating elements. A possible embodiment of this filter can be, but not exclusively, an array of microlenses, an array of Fresnel microlenses or focusing gratings. A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.



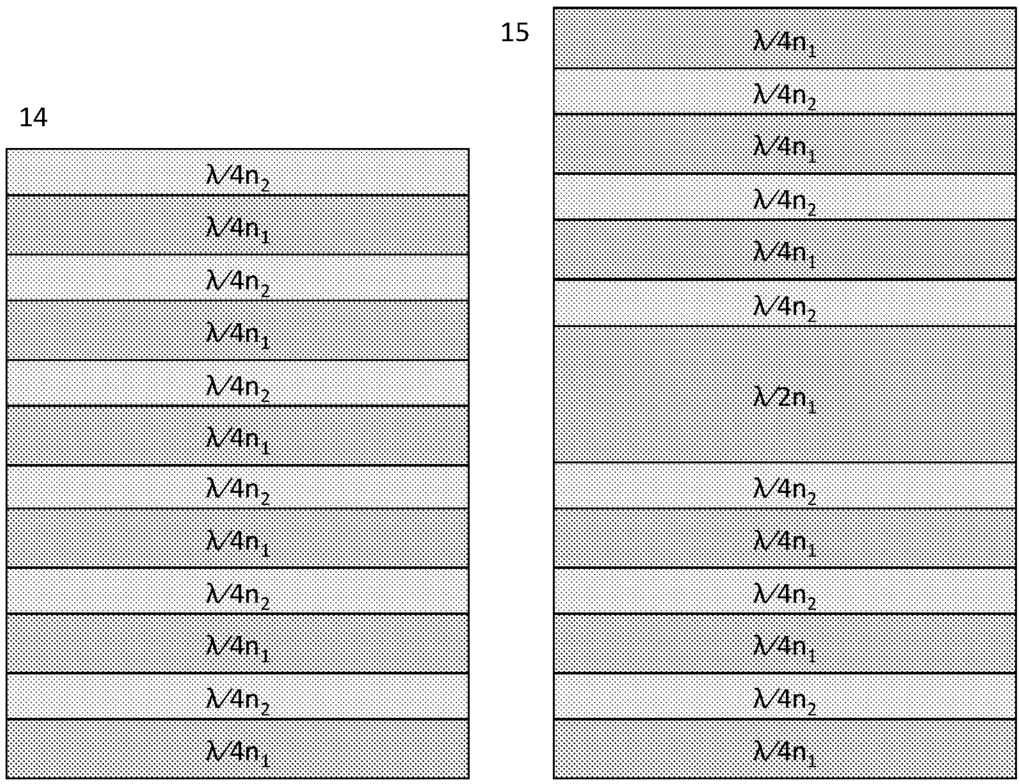
[00016] **Figure 9** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the mirror structure (15) is placed below the substrate (1) and concave shaped, the filter (3) is placed above the emitting structure (2(a), 2(b), 2(c)). A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the mirror layer inside the passband, and therefore be emitted through.



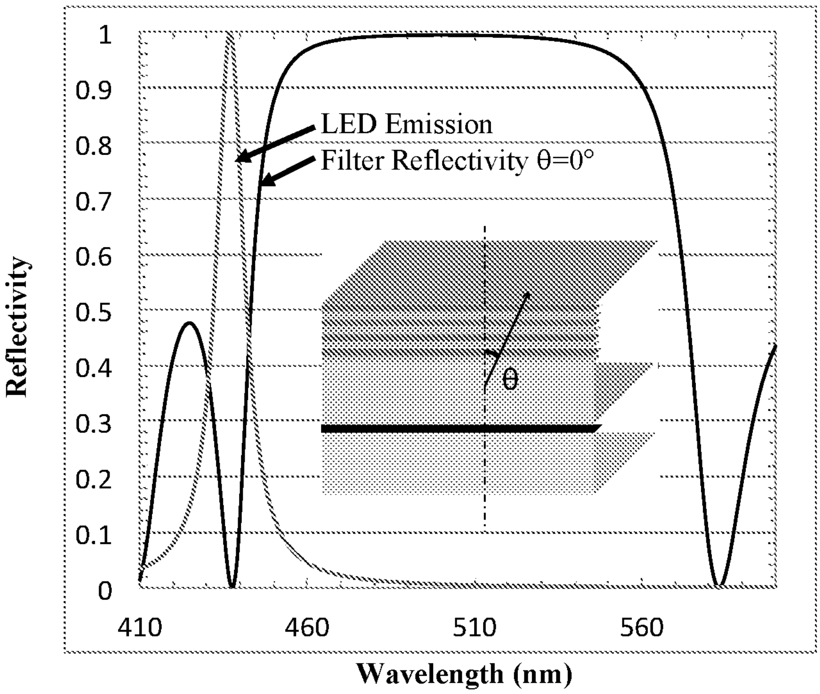
[00017] **Figure 10** illustrates the non-exhaustive variety of possible implementations of the angular bandpass filter. The list comprises for example, but not exclusively, grating structures (10), photonic crystal structures with triangular (11) and square (12) lattice, planar DBR reflector structure (13), planar cavity comprised between two DBR reflector structures (14).



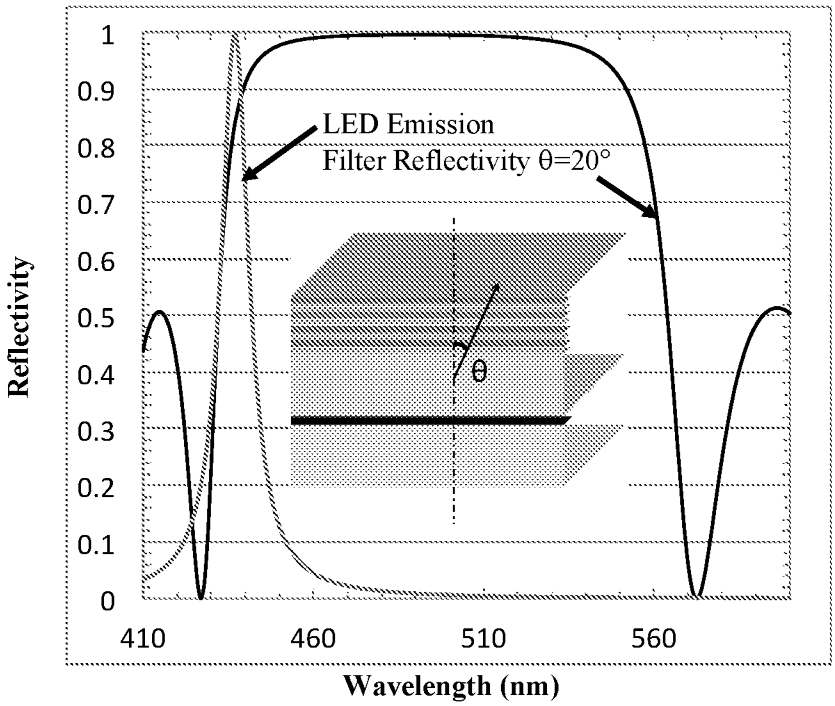
[00018] **Figure 11** depicts in greater details an embodiment of the planar stacks 13 and 14 of figure 5. The structure 14 consists in a stack of pairs of layers which individual optical thicknesses is equal to a quarter wavelength of the light to be filtered. The number of pairs can be varied, indicatively in the present example the stack comprises 6 pairs. Structure 15 consists in a half wavelength cavity sandwiched between 3 pairs of optical thickness of a quarter wavelength, inducing a resonance (cavity mode) at the wavelength of interest. As the relative incidence of the light emitted by the light emitting structure is tuned away from incidence, the effective cavity mode shifts in energy and gets detuned from the light emitting structure, reflecting back the light emitted.



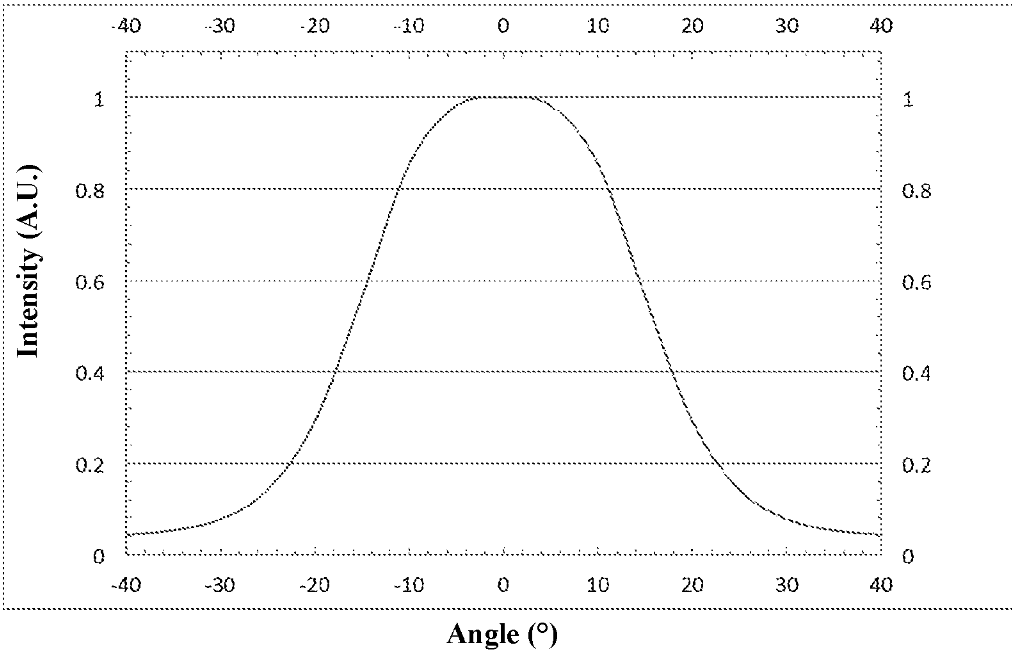
[00019] **Figure 12:** Computed reflectivity patterns of a possible implementation of a filter, consisting in a DBR mirror structure comprising 10 pairs of SiO_2/Si_3N_4 layers, each layer having optical thickness of λ/4. The two reflectivity patterns correspond to an incidence angle of 0° (normal to the surface), in which case the emitting structure emission centered in 435nm corresponds to a first reflectivity minimum immediately after the stop band.



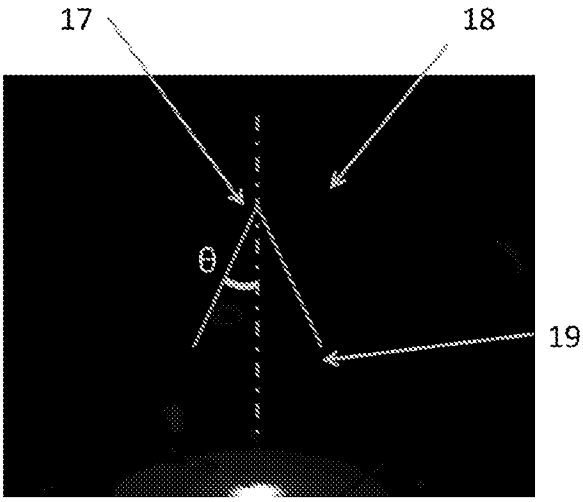
[00020] **Figure 13:** Computed reflectivity patterns of a possible implementation of a filter, consisting in a DBR mirror structure comprising 10 pairs of SiO_2/Si_3N_4 layers, each layer having optical thickness of λ/4. The reflectivity pattern corresponds to a light incidence angle of 20° (with respect to surface normal), in which case the emitting structure emission centered in 435nm is greatly overlapping the DBR band edge, inducing a reflection of most of the light.



[00021] **Figure 14** describes the angular dispersion of the emission of an implantation of the invention. In this example, the angular dispersion is 16°, confirmed by the experiment presented in figure 5. The angular filter is in that case a cavity depicted in figure 5, element 13, and figure 6, element 15.



[00022] **Figure 15:** Picture of an actual implementation of the device similar to the one described in figure 5. The filter consisted in a dielectric cavity comprised between two sets of dielectric DBR mirror stacks. The device (18) was contacted (17), yielding an emission that was projected on a screen (19). The emitted beam appears to be circular, with an angular dispersion lower than θ=± 20°.



DETAILED DESCRIPTION AND BEST MODE OF IMPLEMENTATION

[00023] The following description of the preferred implementation refers to the accompanying drawings shown to describe a specific embodiment in which the invention may be practiced. Other embodiments may be utilized without departing from the scope of the present invention.

[00024] The invention consists in the modification of an LED structure in order to improve its emission directivity with optimum light extraction efficiency. In a configuration where the light is emitted upward, the invention can comprise

a. An LED structure with p-doped and n-doped contact layers to inject current into the emitting region containing the light emitters, possibly quantum wells

b. A filter placed on top of the LED structure, in the course of the output beam, narrowing down the light angular dispersion

c. Diffusing elements, or diffracting elements, or focusing elements, or collimating elements that are placed above, below or inside the LED structure

d. Mirror structures that prevents light from escaping elsewhere than through the said filter

[00025] Figure 2 illustrates the schematics of an LED coupled to a filter that narrows down the emission angular distribution. All the elements of both devices presented in figure 1 and 2 are identical, except for the additional filter present only in the device structure of figure 2. The substrate (1) serves as support for the LED structure consisting in a p-doped contact layer (2a or 2c) and an n-doped contact layer (2c or 2a) respectively, and an active part emitting light comprising quantum wells, quantum wires or quantum dots (2b). The emission of the LED outside the device is depicted (5), only limited by total internal reflection. For the sake of comparison, the limits of passband (4) of the angular bandpass filter (3) are depicted in both schematics. The actual effect of the angular bandpass filter is an angular selection of the output light beam (6), whereas the part of the light that is not within the angular passband is reflected (7). A purpose of the invention is to recycle the light that is reflected (7) in order to improve the extraction efficiency within the angular passband of the filter (3).

[00026] A first step towards the invention is to implement an additional mirror to the structure described in figure 1. Figure 3 shows the course of beam of light emitted by the active region in this case. Despite the additional mirror (8), the light that is rejected by the filter (3) and reflected by the mirror (8) reaches the filter for the second time with the same relative angle and therefore is again rejected.

[00027] The only way to improve light extraction in that case is to implement a diffusing layer depicted in figure 4 as element (9). In this case, a beam that is rejected by the filter, and reaches the diffusing layer, is redirected possibly in a direction that is within the passband of the angular filter (3).

Light emitted by the light emitting light emitting layers 2(b) is isotropic in a first approximation. The part of the light that is emitted downward is reflected by the bottom mirror (8), going back upward. The light emitted upward is reaching the filter (3). The part of the light that is within the angular passband of the filter passes through it and is emitted by the device. The part of the light outside the angular passband of the filter is reflected downward, reaching the diffusing elements (9). The diffusing elements redirect the light, part of it being reflected back towards the filter, part of it passing through the diffusing elements, reaching the bottom mirror. The part of the light reflected back towards the filter gets another chance to be within the angular passband of the filter. The part of the light reaching the bottom mirror is reflected upward, reaching the filter, getting as well another chance of being within the angular passband of the filter. If the light is not within the angular passband, it is reflected again towards the diffusing elements. In this way, iteratively, most of the light emitted initially by the emitting part of the LED will be emitted outside the device. Without the diffusing elements, the light would not be able to go through the filter after another reflection on the bottom mirror, as the relative angle with the filter would not change. The diffusing elements are therefore key to improve light extraction within the angle imposed by the filter.

[00028] The invention is therefore a simple, cost efficient and compact implementation of a device with a low emission angular dispersion and high extraction efficiency, using standard waferscale microfabrication techniques.

[00029] In a configuration, the device structure comprises, among other elements, four main features: the bottom mirror, the diffusing elements, the light emitting structure, and the filter.

[00030] A non-exhaustive list of possible embodiments of the invention are described in figures 4, 5, 6, 7, 8 and 9.

[00031] **Figure 4** shows a possible implementation of the invention that can illustrate its principle. The light rejected by the filter, that is reflected back, is redirected by the diffusing elements, inducing an angle allowing the light to go through the filter. One of these beams is represented (6). The extraction efficiency within the angular passband is therefore increased. Iteratively, in the ideal case where reflectivity of the mirror and that of the filter outside the passband is 1, and the losses within the structure are negligible, all the light produced by the light emitting structure should pass through the filter within its angular passband.

[00032] **Figure 5** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the mirror structure (3) is placed below the substrate (1), the diffusing layer (9) is placed above the emitting structure (2(a), 2(b), 2(c)) and below the angular bandpass filter (8). A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.

[00033] **Figure 6** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the diffusing layer (9) is placed below the substrate (1), between the substrate and the filter (3) the mirror structure (8) is placed above the emitting structure (2(a), 2(b), 2(c)). A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.

[00034] **Figure 7** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the diffusing layer (9) is placed below the emitting structure (2(a), 2(b), 2(c)) and above the mirror (8), the filter structure (3) is placed above the emitting structure. A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.

[00035] **Figure 8** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the mirror structure (8) is placed below the substrate (1), the filter (3) is placed above the emitting structure (2(a), 2(b), 2(c)). The diffusing layer (9) consists in an array of microlenses is placed below the emitting structure. A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the diffusing layer inside the passband, and therefore be emitted through.

[00036] **Figure 9** shows another possible implementation of the invention, based on the same principle as presented in figure 4. In that case, the mirror structure (15) is placed below the substrate (1) and concave shaped, the filter (3) is placed above the emitting structure (2(a), 2(b), 2(c)). A possible beam trajectory is depicted (6) to illustrate the fact that a beam originally outside the passband can be redirected by the mirror layer inside the passband, and therefore be emitted through.

[00037] A non-exhaustive list of possible embodiments of the filter structure are described in figure 10.

[00038] In a possible embodiment, the filter can be a grating (figure 10, element (9)). The grating can be etched in the semiconductor material comprising the emitting layers, or in a material deposited on top of the semiconductor material, or in a material deposited on a sacrificial layer that can be subsequently removed. The grating properties are such that it constitutes an angular bandpass filter. In an embodiment, the periodicity Λ and filling factor a/Λ of the grating structure is adapted in such a way that the emission wavelength of the light generating layers falls within the second stopband of the said grating structure, allowing for two leaky modes, one colinear to the plane of the grating, and the other perpendicular to the plane of the grating. In another embodiment following the same design principles, the grating can be of circular symmetry.

[00039] In an embodiment, the filter can be photonic crystals. The elements 10 and 11 in figure 10 are photonic crystals with square and triangular lattices, respectively. In this implementation, the base wafer on which the material constituting the filter structure is deposited can for example, but not exclusively be GaN or sapphire in the

case of a III-N based LED, or GaAs in the case of a III-As based LED. In a configuration, the material constituting the filter can be completely etched outside the emitting region, down to the base wafer. Subsequent epitaxial growth can be performed, until coalescence above the filter. The LED structure can be subsequently grown, and the top mirror structure implemented on top of it. The photonic crystals have properties such that the incident light passes through at angles close to normal incidence, and is redirected for larger angles up to a certain angle beyond which light is totally reflected back. Such conditions are met for example, in the case of a triangular lattice, for a pitch Λ of 325nm and a fill factor of 70%, when a=150nm deep cylindrical holes are etched into GaN.

[00040] In a possible implementation, the filter structure can be made of a single epitaxially grown DBR comprising a certain number of pairs of semiconductor material. The base semiconductor material composing the LED can be, but is not limited to, III-N semiconductors, III-As semiconductors, or III-P semiconductors. The semiconductor material composing the pairs can be for example, but not limited to $Al_xGa_{1-x}N$/ $Al_yGa_{1-y-z}In_zN$, with $0<x<1$, $0<y<1$, $0<z<1$, $Al_xIn_{1-x}N$/ $Al_yGa_{1-y-z}In_zN$, with $0<x<1$, $0<y<1$, $0<z<1$, $Al_xGa_{1-x}As$/ $Al_yGa_{1-y}As$, with $0<x<1$ and $0<y<1$. The semiconductor material composing the pairs can also be for example, but not limited to, any combination of III-V semiconductors providing refractive index contrast with moderate lattice mismatch.$_y$ In another implementation, the filter structure consists in an amorphous or crystalline dielectric DBR. The DBR can consist in an ensemble of pairs of layers with alternated material with different refractive index. Each pair can for example, but not exclusively, be made of SiO_2 and TiO_2, or SiO_2 and Si_3N_4, or any material with different refractive index. In order to operate as an angular filter, the wavelength of light emitted by the light emitting layers has to match the first minimum of reflectivity immediately above the stopband, in energy (figure 12). For angles different than normal incidence, the band edge is shifted towards higher energies, reflecting back the light emitted by the light emitting layers (figure 13). Indicatively, an incidence of 20° with respect to normal shifts by 8nm the position of a 4 pair DBR stack of $\lambda/4n$ SiO2/Si_3N_4 optimized to have a band edge at 437nm, corresponding to a damping of nearly 75% of a Lorentzian emission with 10nm full width at half maximum.

[00041] In an embodiment, the filter is a cavity comprised between two stacks of DBR pairs, such as depicted in figure 11 (15). A tradeoff can be found between angular dispersion and extraction efficiency, by shifting the LED emission with respect the cavity mode of the filter. Simulations suggest that in the case of an SiO_2 cavity sandwiched between two DBR mirrors comprising 4 SiO_2/Si_3N_4 pairs each, having a resonance at 430nm, a Lorentzian emission of the light emitters centered in 430nm with a FWHM of 10nm, the angular dispersion is ±16°, and the extraction efficiency is approximately 70%. The angular distribution of the light emitted by the said device is computed in figure 14, and figure 16 shows a picture of an actual implementation of the device. The device (18) was contacted (17), yielding an emission that was projected on a screen (19). The emitted beam appears to be circular, with an angular dispersion lower than $\theta=\pm$ 20°.

[00042] Introducing a mismatch of 8nm between the LED emission and the cavity mode, the angular dispersion is ±25°, and the extraction efficiency close to 90%.

[00043] In a configuration, the diffusion layer is formed on top of the LED structure. The diffusion layer can for example consist in a layer of high rugosity that will diffuse light. The rugosity can consist in a random or ordered pattern.

A possible implementation of the diffusing layer, in the case of GaN-based structure, consists in using a chemical solution after prior protection of all the surfaces except the one that is to be roughened. The chemical solutions can be for example, but not exclusively KOH, or a mixture of $K_2S_2O_8$ and KOH, or a mixture of H2O2 and citric acid.

In another implementation, the photoassisted anodic etching can be used, involving for example, but not exclusively, a mixture of tartaric acid and ethylene glycol.

In another implementation, Inductive Coupled Plasma (ICP) can be used, possibly, but not exclusively, with a mixture of BCl_3, Cl_2 and Ar in a variety of proportions, in particular, but not exclusively, with a substrate temperature greater than 30°C, inducing a GaN surface particularly rough.

In another implementation, the base material is GaAs. In that case, the chemical solutions inducing the surface roughening can be for example, but not exclusively, H_2SO_4, H_3PO_4, a mixture of H_2O_2 with H_2SO_4, H_3PO_4, HCl, a mixture of methanol with Br or HBr, The ICP gases can be, but not exclusively, BCl_3, Cl_2, Ar, O_2.

In another implementation, the base material is GaP. In that case, the chemical solutions inducing the surface roughening can be for example, but not exclusively, a mixture of HCl and HNO_3 and Br, a mixture of $AgNO_3$ and Cr O_3 and H_2O. The ICP gases can be, but not exclusively, BCl_3, Cl_2, Ar, O_2.

In another implementation, a first step consists in patterning a polymer layer by for example, but not exclusively photolithography, ebeam lithography, nanoimprint lithography. The pattern can be random or well defined. Subsequently, the above-mentioned etching methods can be used for example, but not exclusively.

A more comprehensive list of etchants that can possibly, but not exclusively is presented in Clawson, *Materials Science and Engineering*, **31** 1-438 (2001).

[00044] In a configuration, the diffusion layer consists in periodic subwavelength structures such as, but not limited to, photonic crystals or gratings. These structures can be implemented by e-beam lithography of a polymer, and subsequent transfer to a hard mask, such as, but not limited to, dielectric amorphous material (SiO_2, SiN ...), and then from the hard mask the pattern can be transferred to the semiconductor substrate, or any substrate on which the LED structure is grown.

[00045] In a configuration, the diffusing layers consisting in planar gratings or photonic crystals have such properties that light is reflected back with a certain angle that is within the angular passband of the filter.

[00046] In a configuration, the diffusion layer is subsequently smoothened, possibly with spin-on-glass. Finally, a mirror structure, that can consist in a dielectric DBR structure, of reflective metal, or a planar grating or photonic crystal structure, is implemented, to complete the structure. Subsequent processing of the device can then be performed.

[00047] The extraction efficiency of the present invention is only limited by

- The finite transmission of the filter
- The finite reflectivity of the mirror structures
- The losses in the region between the mirror and the filter
- The losses within the filter

For state of the art parameters, the main source of losses is the finite transmission of the filter. In the implementation where the filter is a cavity, a tradeoff can be found between angular dispersion and yield, by shifting the LED emission wavelength with respect the cavity mode of the filter. Simulations and experiments suggest that in the case of an SiO_2 cavity sandwiched between two DBR mirrors comprising 4 SiO_2/Si_3N_4 pairs each, having a resonance at 430nm, a Lorentzian emission of the light emitters centered in 430nm with a FWHM of 10nm, the angular dispersion is ±16°, and the yield is approximately 70%.

Introducing a mismatch of 8nm between the LED emission and the cavity mode, the angular dispersion is ±25°, and the yield close to 90%.

CLAIMS

What is claimed

1. A device comprising
   - An emitter of light
   - A structure able to diffuse light
   - An angular bandpass filter
   - A reflector
2. A device according to claim 1, wherein the emitter of light is a light emitting diode (LED) or a micro LED
3. A device according to claim 2, wherein the structure able to diffuse light is a material made minutely rough, and consequently lusterless, so that light passing through, or reflected by, its surface, is diffused in a plurality of directions
4. A device according to claim 2, wherein the structure able to diffuse, diffract, focus or collimate light is a grating
5. A device according to claim 2, wherein the structure able to diffuse, diffract, focus or collimate light is a photonic crystal structure
6. A device according to claim 3,4 or 5, wherein the angular bandpass filter is a grating structure, or a photonic crystal structure, or a planar Distributed Bragg Reflector (DBR) mirror, or a cavity comprised between two DBR mirror structures, or any dielectric layer stack
7. A device according to claim 6, wherein the mirror is a planar DBR mirror structure, a grating structure, or a photonic crystal structure, or a metallic layer.
8. The device according to claim 2 can be arranged into matrices

MANUFACTURING

Method 1:

1. Form an active layer on a substrate
2. Form a dielectric layer
3. Increase roughness of the said dielectric layer
4. Planarise the surface with a material having a lower refractive index
5. Form a mirror on the planarised layer
6. Etch through the mirror layer to reach the contact layers
7. Form contacts
8. On the back of the substrate, for an angular bandpass filter

Method 2:

1. Form a light emitting structure on a substrate
2. Form a grating structure on the light emitting structure
3. Planarise the surface with a material having a lower refractive index
4. Form a mirror on the planarised layer
5. Etch through the mirror layer to reach the contact layers
6. Form contacts
7. On the back of the substrate, for an angular bandpass filter

Figure 1

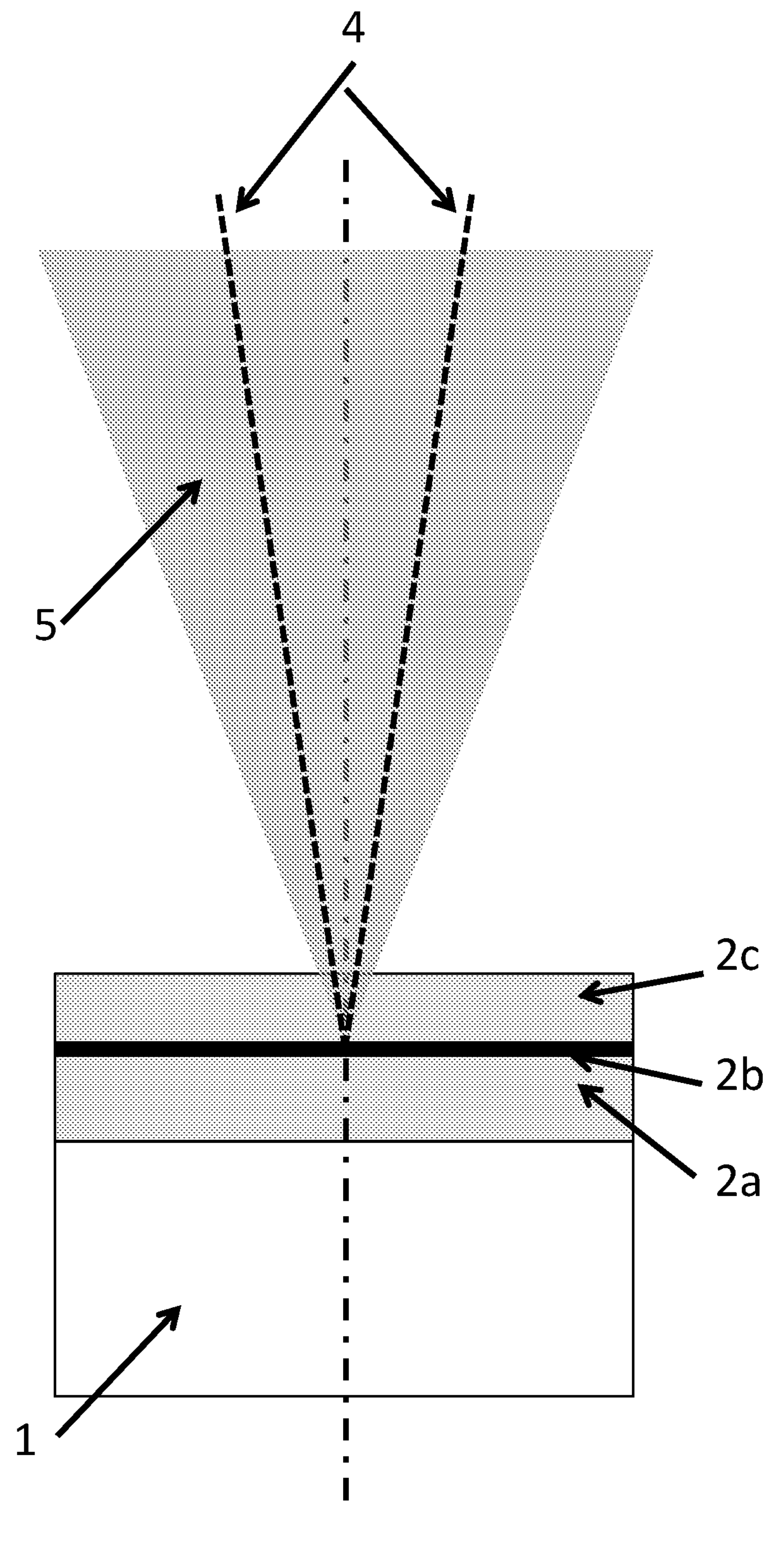


Figure 2

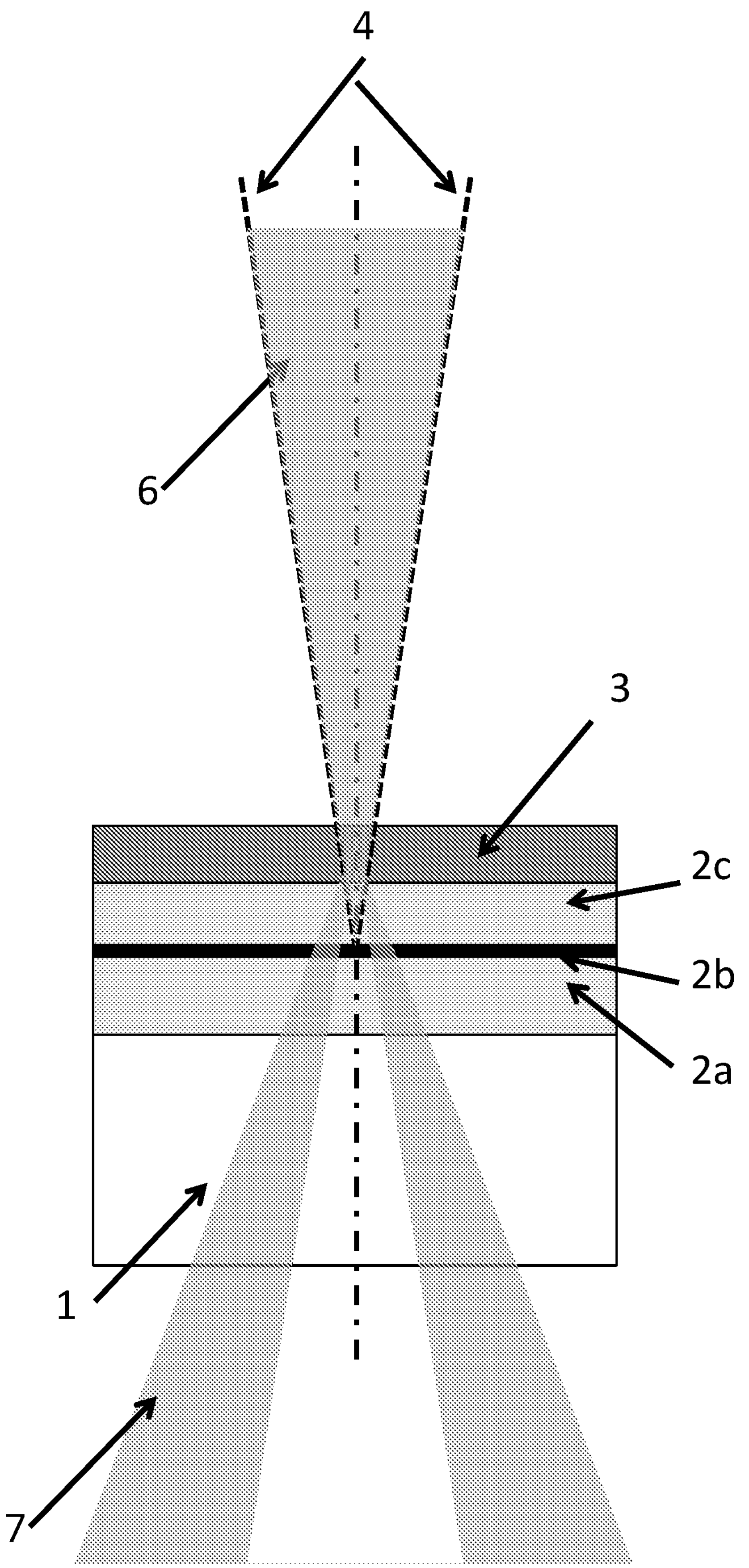


Figure 3

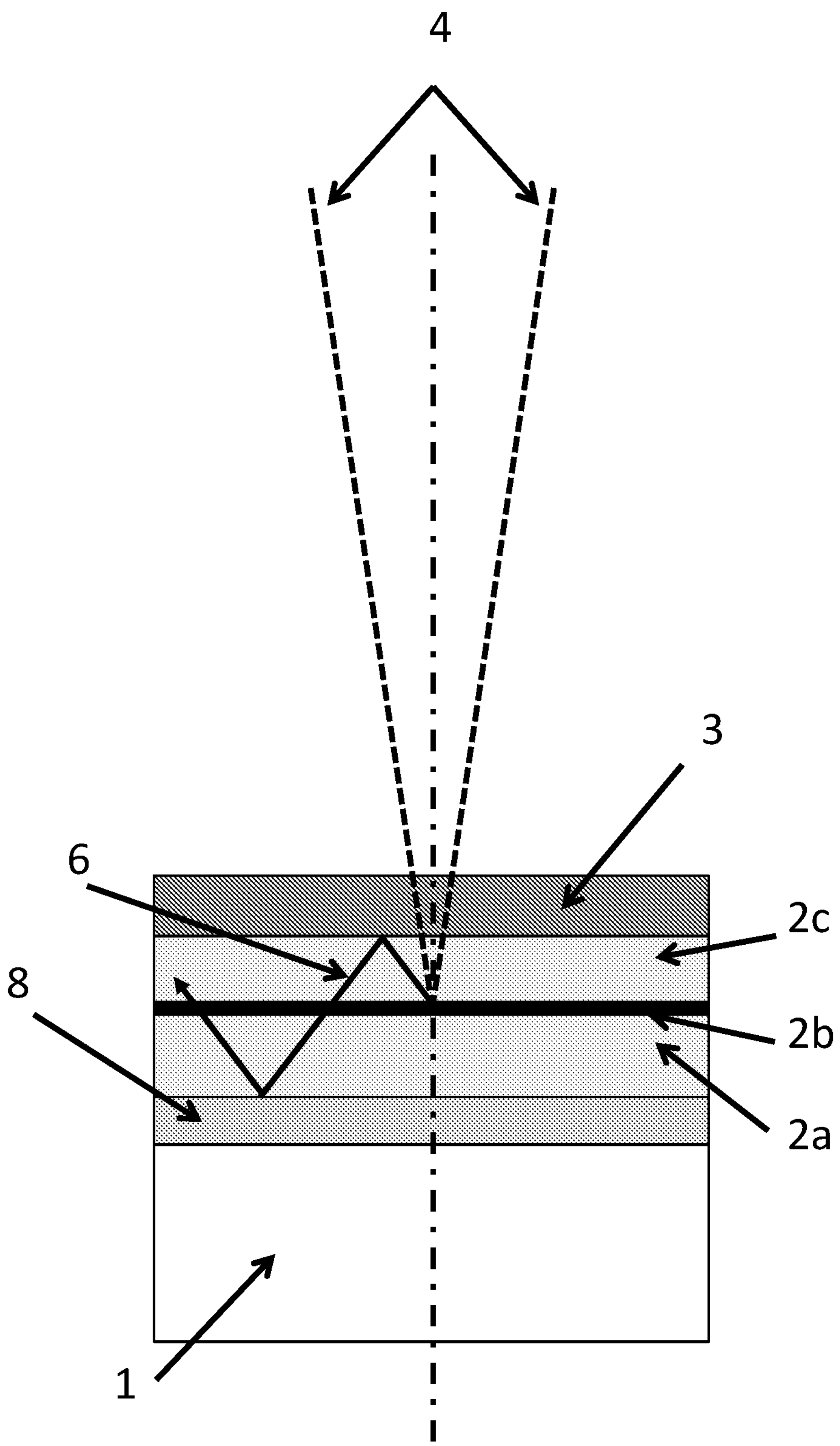
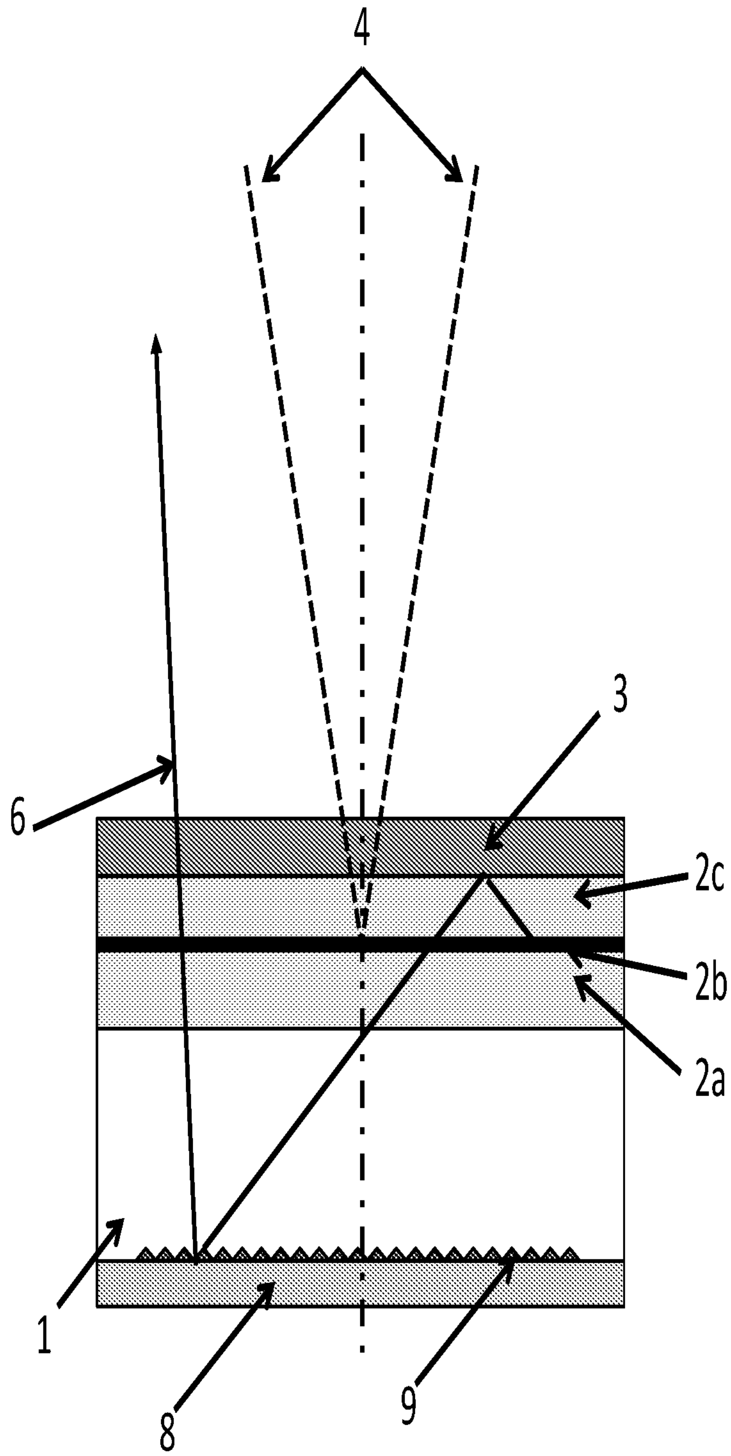


Figure 4



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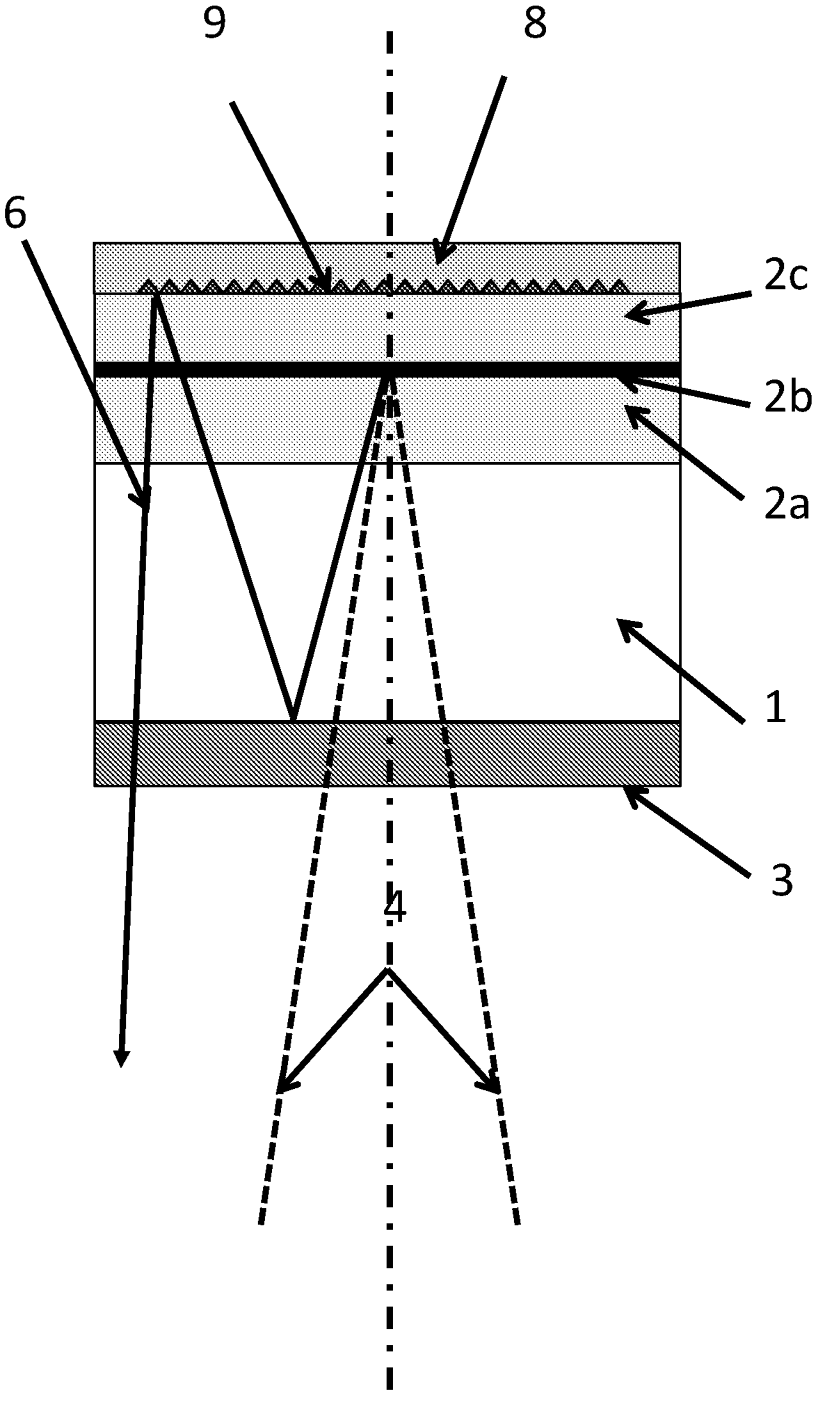


Figure 6

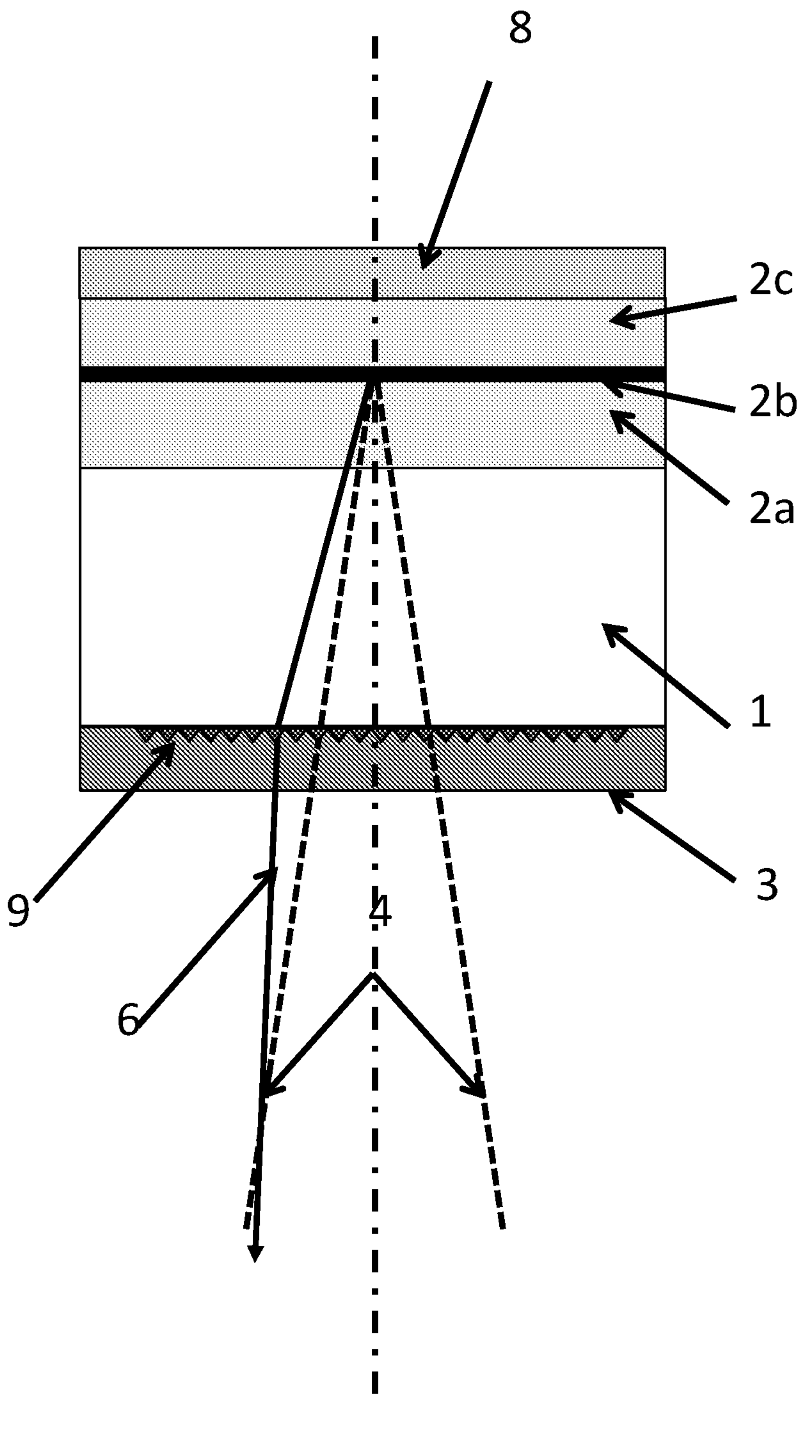


Figure 7

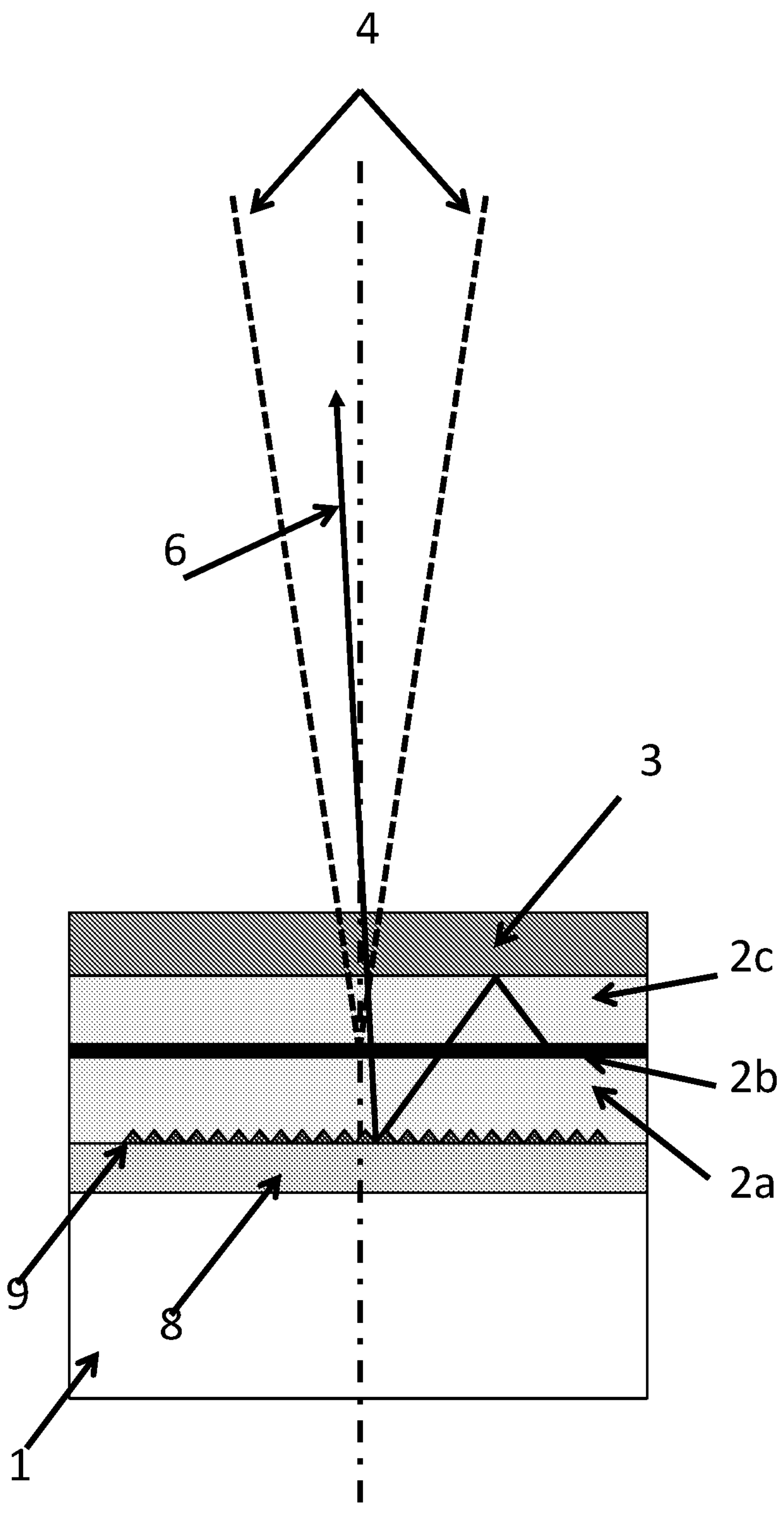
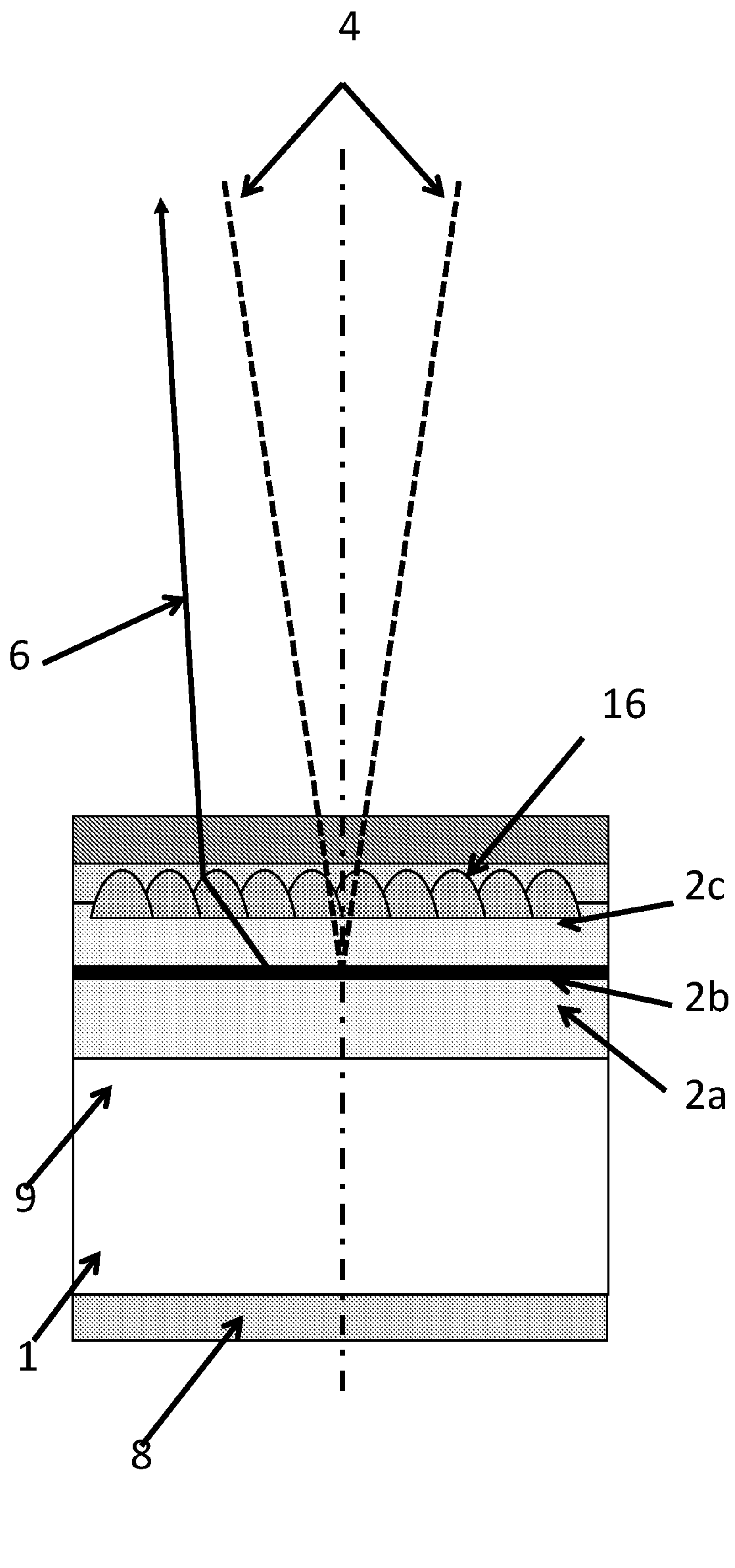


Figure 8



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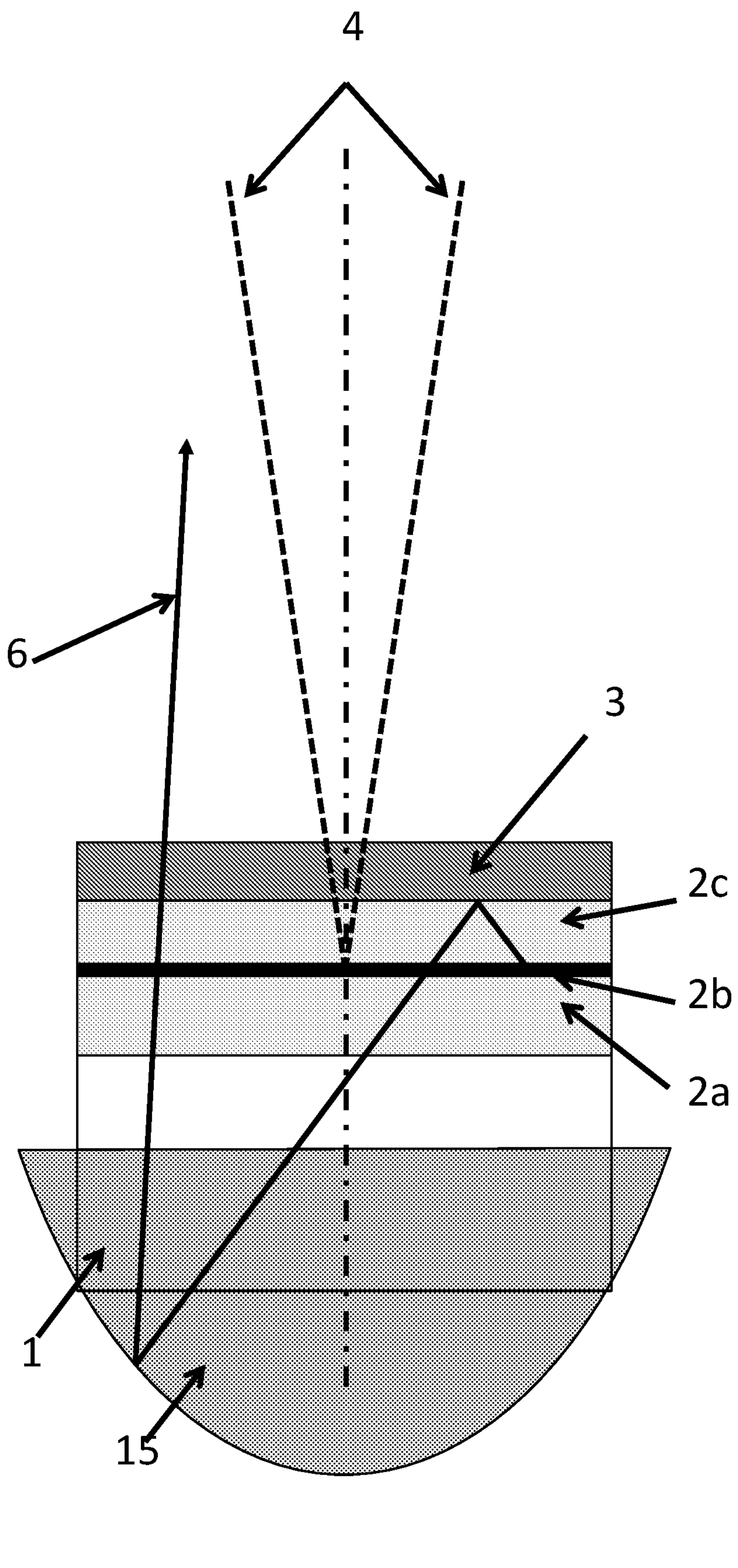

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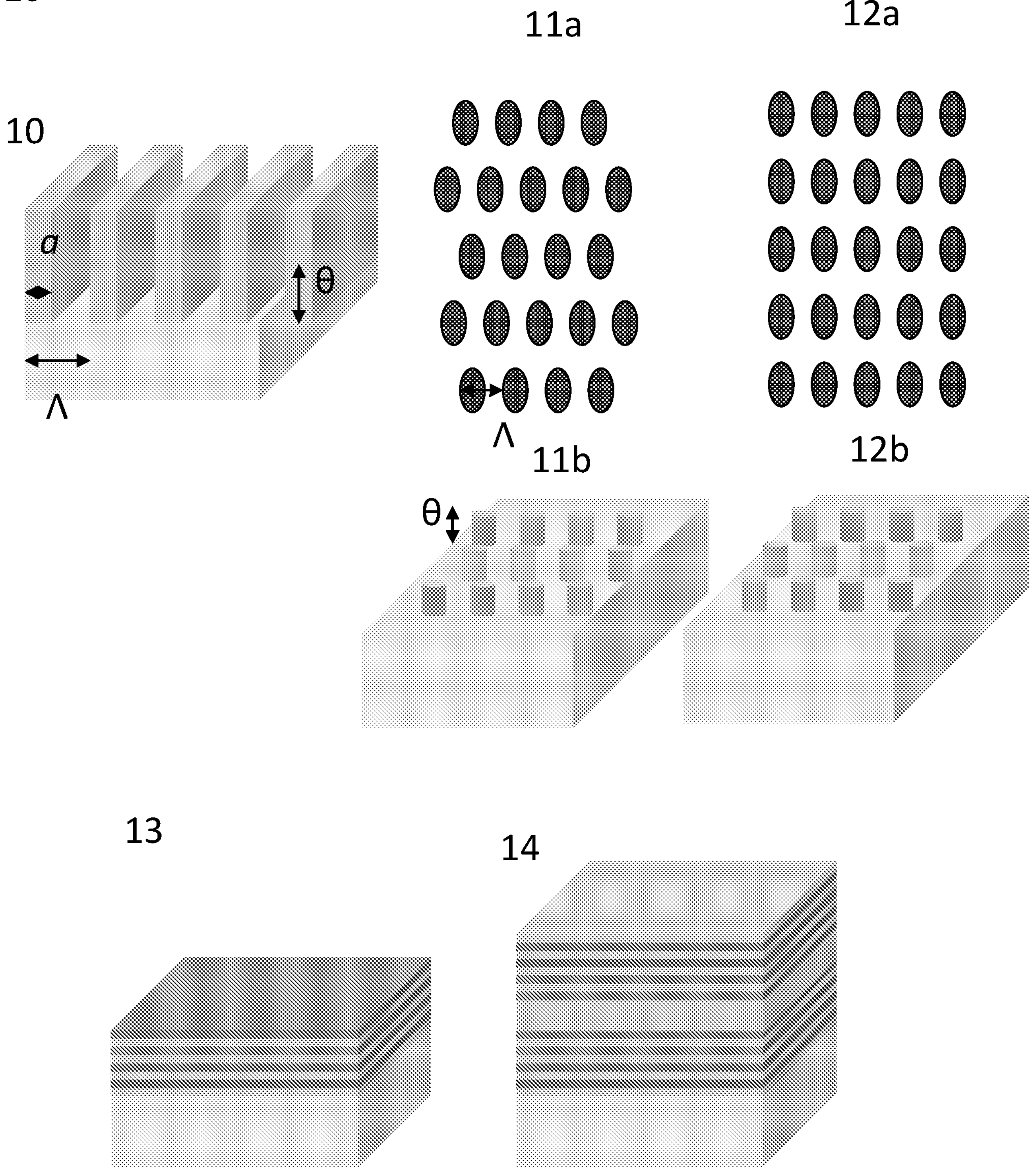

Figure
11

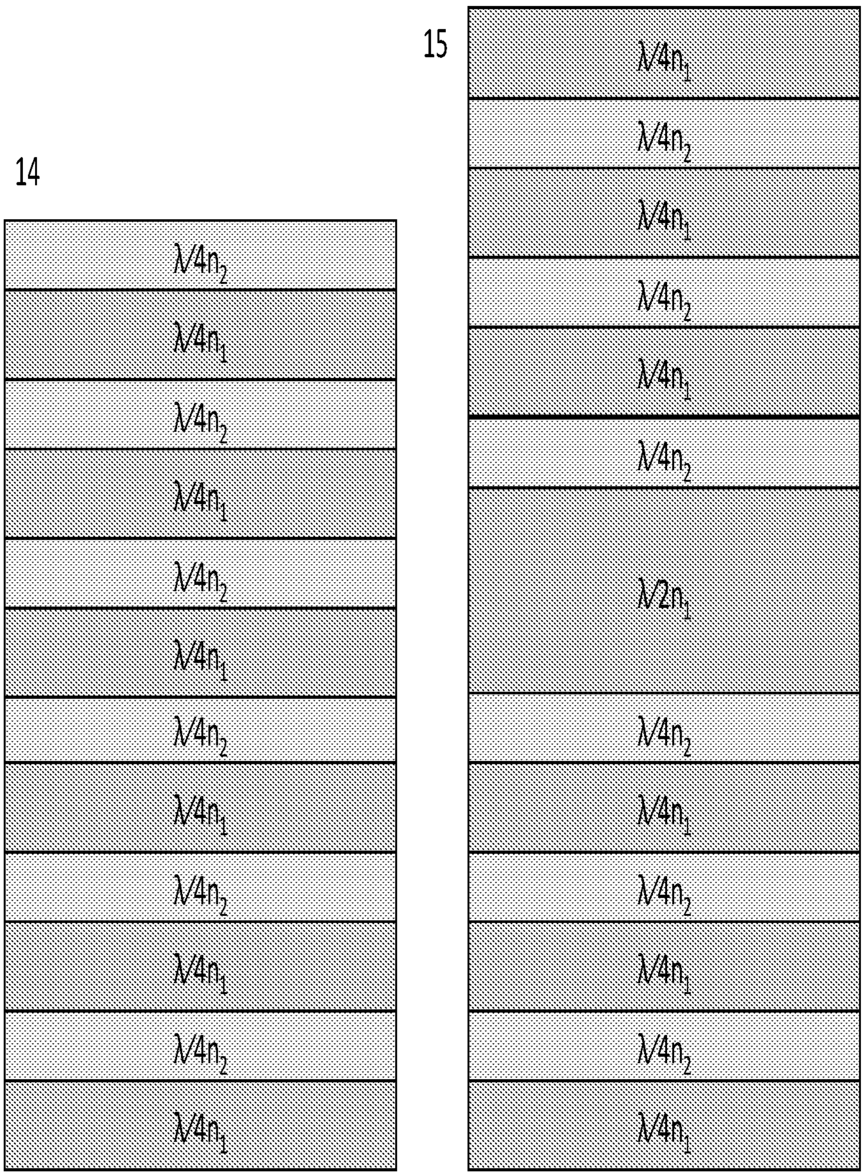
15
λ/4n1
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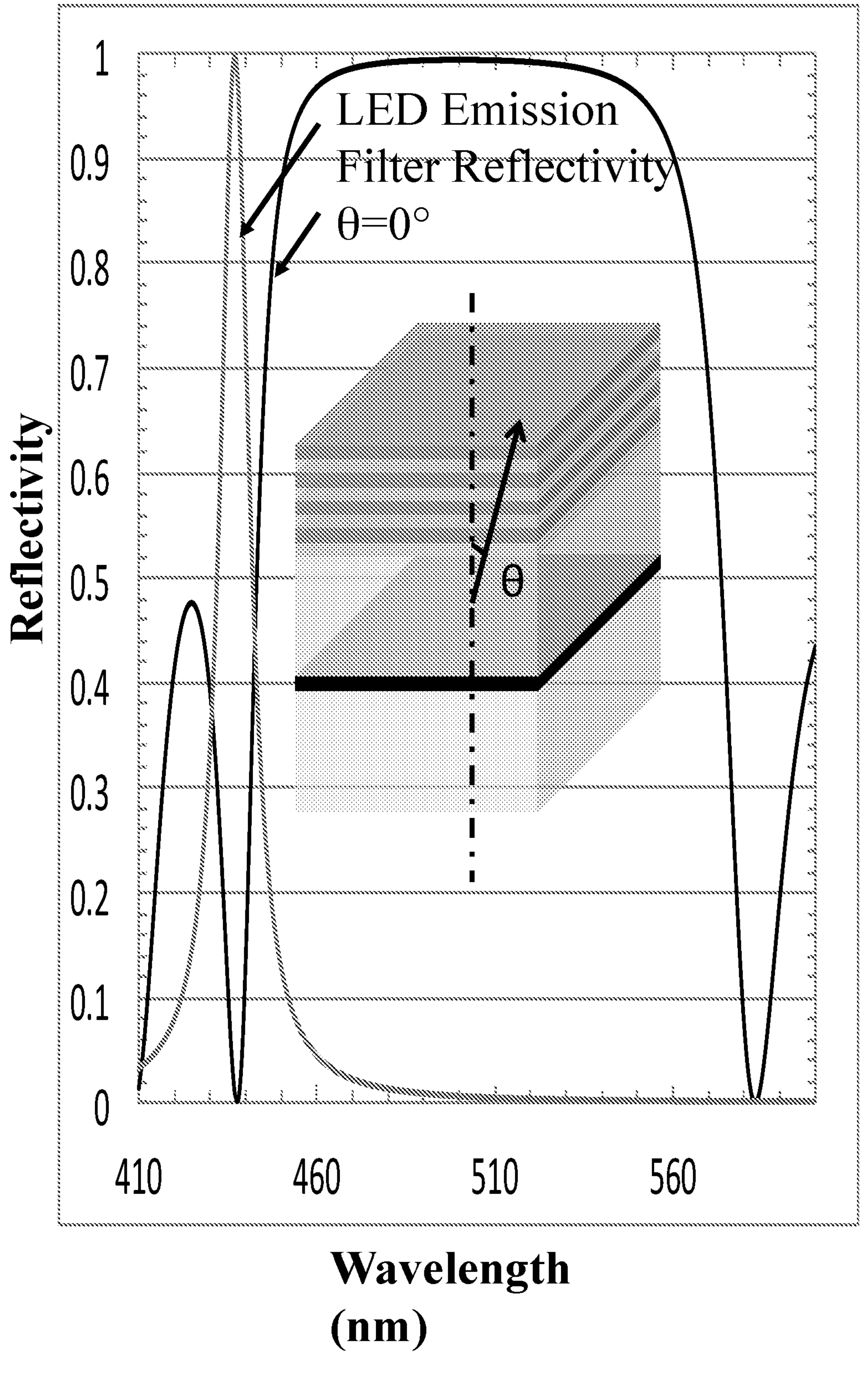
Figure 12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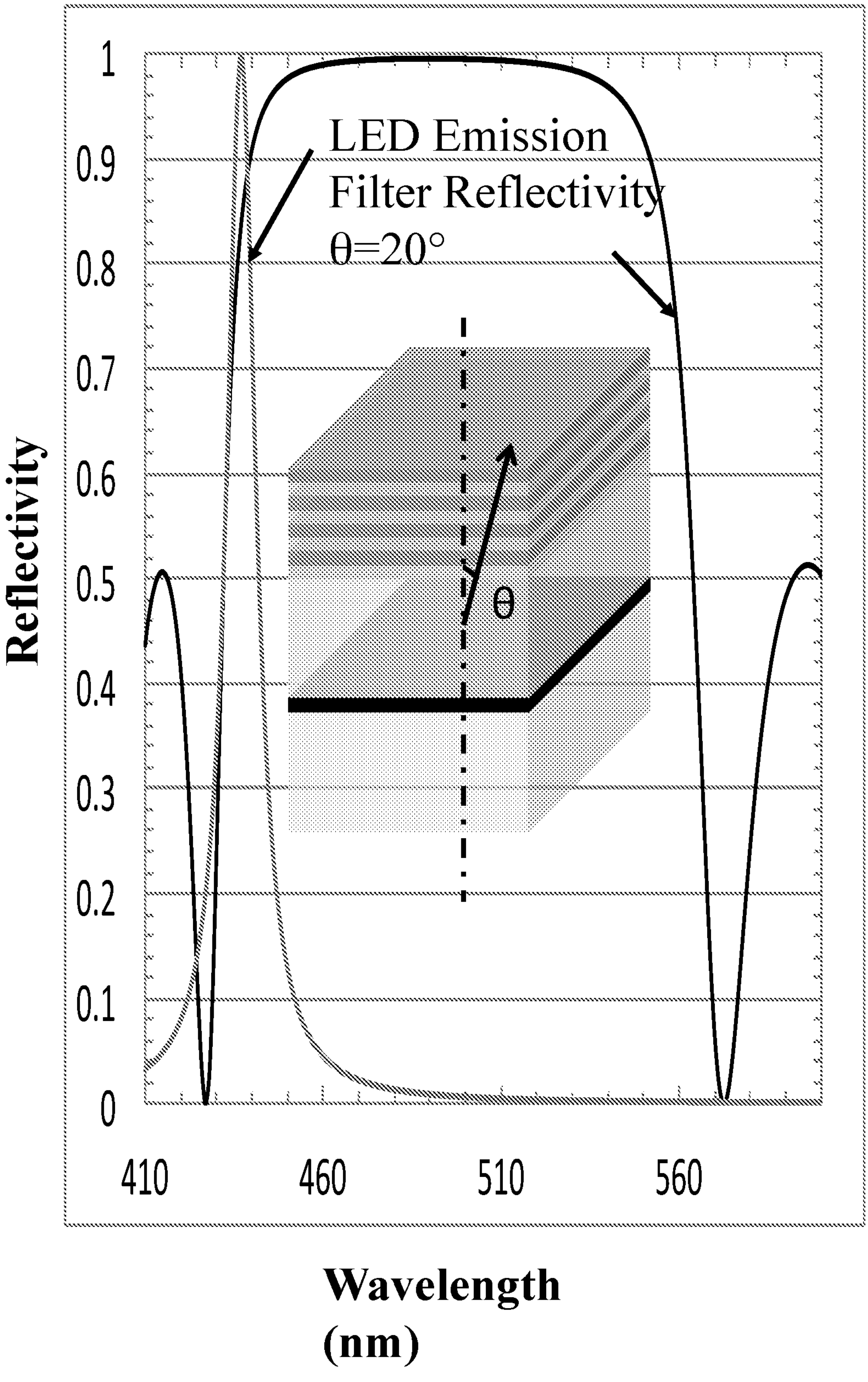
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
410
460
510
560
Reflectivity
LED Emission
Filter Reflectivity
θ=0°
θ
Wavelength (nm)

Figure 13


1
0.9
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0.3
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Reflectivity
LED Emission
Filter Reflectivity
θ=20°
θ
410
460
510
560
Wavelength
(nm)

Figure 14

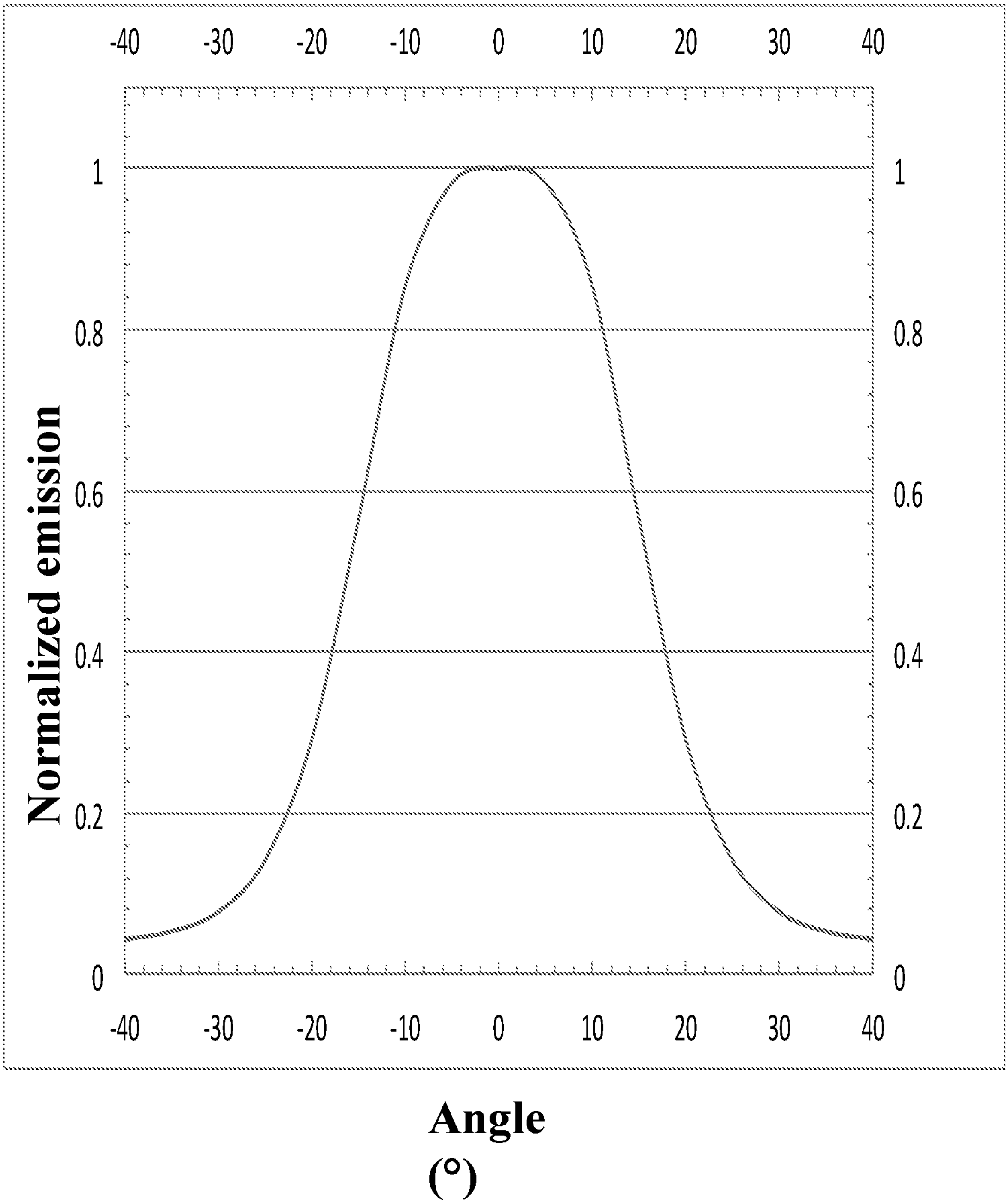
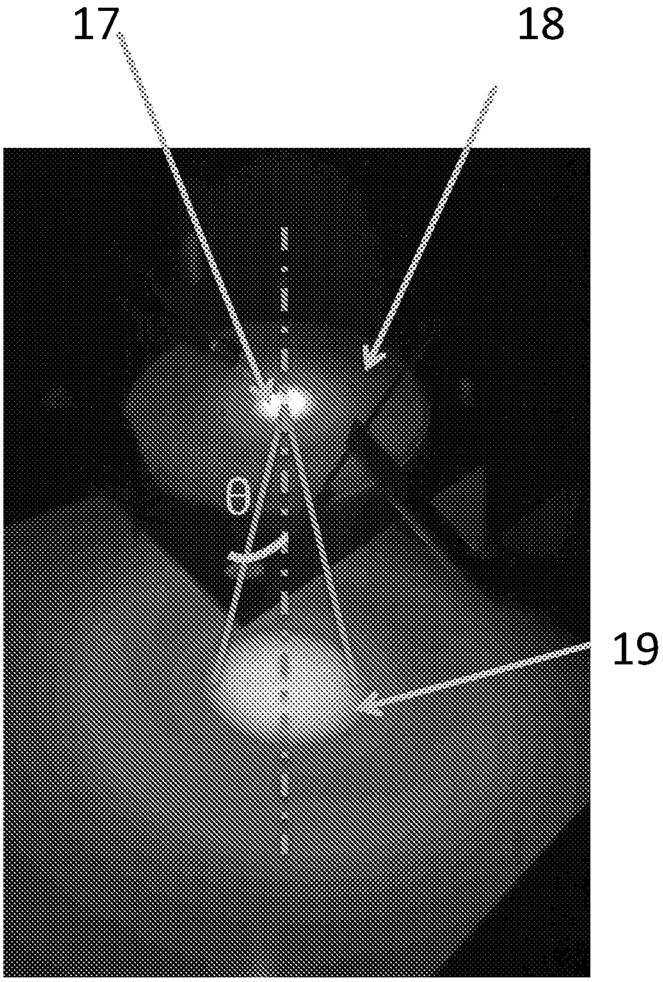

-40
-30
-20
-10
0
10
20
30
40
1
0.8
0.6
0.4
0.2
0
Normalized emission
Angle
(°)

Figure
15



INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2017/051946

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L33/22
ADD.

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

B. FIELDS SEARCHED

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

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/035944 A1 (EBERHARD FRANZ [DE] ET AL) 14 February 2008 (2008-02-14)	1-8
Y	abstract; figures 1,2,5,6,14 paragraphs [0007] - [0021], [0025], [0028], [0029], [0039], [0040], [0075] - [0081], [0091] - [0098], [0115], [0119], [0120] -----	4-7,9,10
X	US 2007/284567 A1 (POKROVSKIY ALEXANDER L [US] ET AL) 13 December 2007 (2007-12-13)	1-3,8
Y	abstract; figures 1,8,23a paragraphs [0059] - [0063], [0083] - [0085], [0165] - [0169] -----	4,5,9

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 September 2017	19/09/2017

Name and mailing address of the ISA/	Authorized officer
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1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 5 779 924 A (KRAMES MICHAEL R [US] ET AL) 14 July 1998 (1998-07-14) abstract; figures 1,11,13,14 column 2, line 65 - column 3, line 10 column 5, line 9 - column 6, line 5 column 6, line 66 - column 7, line 10 column 9, line 5 - column 9, line 24 -----	1,2,8 4-7,9,10
X	US 2010/301369 A1 (DAVID AURELIEN J F [US] ET AL) 2 December 2010 (2010-12-02) abstract; figures 3,5a,8,9 paragraphs [0015], [0046], [0047], [0054], [0057], [0058], [0061] -----	1,2,8

1

INTERNATIONAL SEARCH REPORT

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International application No
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