

A Waveguide Structure And A Method Of Coupling Light

FIELD OF INVENTION

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The present invention relates broadly to a planar waveguide structure and to a method of coupling light into or out of a planar waveguide structure.

10 BACKGROUND

To couple light between a light emitting element or a light receiving element and an optical waveguide, there is typically a problem of low light coupling efficiency. A number of current solutions for light coupling are discussed below.

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Diffraction gratings have been used to change the light direction by diffraction and allow changing the incident light angle to a desired direction. However, diffraction gratings are limited to specific wavelengths of light. Also, the coupling efficiency between the light source and the waveguide is typically low in applications
20 utilizing diffraction gratings.

45-degree mirrors have also been used to change the light direction by 90 degrees via reflection. However, the coupling efficiency between the light source and the waveguide is typically low in applications utilizing such mirrors. Furthermore, as
25 the accuracy of mirror angle, position and surface flatness can affect the coupling efficiency, it is typically more difficult to use 45-degree mirrors.

It is appreciated that alignment of mirrors or reflectors is typically a problem. In US 6473220, JP2008216936 and EP1102096, various reflectors are used to
30 change light direction. However, in these documents, mirror angle and therefore mirror alignment is crucial in achieving the results desired.

Prism coupling has been used for phase matching between a propagation constant and incident light using high index prism. However, prisms are typically expensive and a degree of alignment is still required for light coupling. Further, an evanescent wave method has also been used whereby a propagation mode is excited to facilitate light coupling. However, such a method uses a very thin waveguide and is typically not efficient.

In view of the above, there exists a need for a planar waveguide structure and a method of coupling light into or out of a planar waveguide structure that seek to address at least one of the above problems.

SUMMARY

In accordance with an aspect of the present invention, there is provided a planar waveguide structure, the structure comprising an array of first light reflective structures formed in a first medium of the planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure for reflecting light into a second medium of the planar waveguide structure; an array of second light reflective structures formed in the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure; wherein the second angle θ_2 and the first angle θ_1 are inter-related for propagating light via internal reflection in the second medium.

The array of the second light reflective structures may be formed as a textured surface of the second medium.

The textured surface may be disposed at an interface between the second medium and a third medium of the planar waveguide structure.

The textured surface may comprise a micromirror array.

The array of first reflective structures may be disposed at an interface between the first medium and the second medium.

- 5 A filler medium of each first reflective structure may have a lower refractive index than the first medium.

The filler medium of each first reflective structure may comprise air.

- 10 A filler medium of each second reflective structure may have a lower refractive index than the second medium.

The filler medium of each second reflective structure may comprise air.

- 15 θ_2 may be based on a first constraint

$$90 - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right) - \tan^{-1}\left(\frac{1}{L_2/h_2 - 1/\tan\theta_2}\right) \geq 2\theta_2$$

- where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.
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θ_2 may be based on a second constraint

$$2\theta_2 \geq \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right)$$

- where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.
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Each first light reflective structure may be formed with a base length of between about 2 μm to about 20 μm .

Each second light reflective structure may be formed with a base length
5 between a range of about 4 μm to about 200 μm .

The second medium may be formed as a waveguide with a thickness in a range of about 50 μm to about 200 μm .

10 In accordance with another aspect of the present invention, there is provided a method of coupling light into or out of a planar waveguide structure, the method comprising using an array of first light reflective structures formed in a first medium of the planar waveguide structure to reflect light into a second medium of the planar waveguide structure, each first light reflective structure having a first surface with a
15 first angle θ_1 relative to a longitudinal plane of the planar waveguide structure; using an array of second light reflective structures formed in the second medium to propagate light via internal reflection in the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure; and wherein the second angle
20 θ_2 and the first angle θ_1 are inter-related.

The array of the second light reflective structures may be formed as a textured surface of the second medium.

25 The textured surface may be disposed at an interface between the second medium and a third medium of the planar waveguide structure.

The textured surface may comprise a micromirror array.

30 The array of first reflective structures may be disposed at an interface between the first medium and the second medium.

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A filler medium of each first reflective structure may have a lower refractive index than the first medium.

The filler medium of each first reflective structure may comprise air.

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θ_2 may be based on a first constraint

$$90 - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right) - \tan^{-1}\left(\frac{1}{L_2/h_2 - 1/\tan\theta_2}\right) \geq 2\theta_2$$

where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

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θ_2 may be based on a second constraint

$$2\theta_2 \geq \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right)$$

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where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

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Each first light reflective structure may be formed with a base length of between about 2 μm to about 20 μm .

Each second light reflective structure may be formed with a base length between a range of about 4 μm to about 200 μm .

5 The second medium may be formed as a waveguide with a thickness in a range of about 50 μm to about 200 μm .

10 In accordance with yet another aspect of the present invention, there is provided a method of forming a planar waveguide structure, the method comprising forming an array of first light reflective structures in a first medium of the planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure for reflecting light into a second medium of the planar waveguide structure; forming an array of second light reflective structures in the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure; wherein the second angle θ_2 and the first angle θ_1 are inter-related for propagating light via internal reflection in the second medium.

20 The method may comprise forming the array of the second light reflective structures as a textured surface of the second medium.

25 The method may further comprise forming the textured surface at an interface between the second medium and a third medium of the planar waveguide structure.

The method may further comprise forming the textured surface comprising a micromirror array.

30 The method may comprise forming the array of first reflective structures at an interface between the first medium and the second medium.

A filler medium of each first reflective structure may have a lower refractive index than the first medium.

The filler medium of each first reflective structure may comprise air.

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A filler medium of each second reflective structure may have a lower refractive index than the second medium.

The filler medium of each second reflective structure may comprise air.

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θ_2 may be based on a first constraint

$$90 - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right) - \tan^{-1}\left(\frac{1}{\frac{L_2}{h_2} - \frac{1}{\tan\theta_2}}\right) \geq 2\theta_2$$

where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

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θ_2 may be based on a second constraint

$$2\theta_2 \geq \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right)$$

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where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

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The method may further comprise forming the first light reflective structure with a base length of between about 2 μm to about 20 μm .

The method may further comprise forming the second light reflective structure with a base length between a range of about 4 μm to about 200 μm .

5 The method may further comprise forming the second medium as a waveguide with a thickness in a range of about 50 μm to about 200 μm .

In accordance with another aspect of the present invention, there is provided a planar waveguide structure, the structure comprising an array of first light reflective structures formed in a first medium of the planar waveguide structure, each first light
10 reflective structure having a first surface with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure for reflecting light propagating in the planar waveguide structure out of the first medium into a second medium of the planar waveguide structure; an array of second light reflective structures formed in the second medium, each second light reflective structure having a second surface with
15 a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure for reflecting light out of the second medium.

In accordance with another aspect of the present invention, there is provided a method of coupling light out of a planar waveguide structure, the method
20 comprising using an array of first light reflective structures formed in a first medium of the planar waveguide structure to reflect light propagating in the planar waveguide structure out of the first medium into a second medium of the planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure; using an array of
25 second light reflective structures formed in the second medium to reflect light out of the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

5 Figure 1 is a schematic diagram illustrating a light coupling device in an example embodiment.

Figure 2 is an exploded view of a box in Figure 1.

10 Figure 3 is a schematic diagram illustrating light reflection in a first medium in an example embodiment.

Figure 4 is a schematic diagram illustrating light reflection in the second medium in an example embodiment.

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Figure 5 shows internal reflection of light at an interface between a first medium and a second medium in an example embodiment.

Figure 6 is a graph for constraints 1 and 2 in an example embodiment.

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Figure 7(a) is a graph showing beam width and beam distance results as base size of a first reflective structure varies in an example embodiment.

25 Figure 7(b) is a graph showing reflection efficiency as a base size of a first reflective structure varies in an example embodiment.

Figure 8(a) is a graph showing reflection efficiency and relative shift results as base size of a second reflective structure varies in an example embodiment.

30 Figure 8(b) is a graph showing coupling efficiency results as the base size of a second reflective structure varies in an example embodiment.

Figure 9 is a graph showing constraints 1 and 2 results using exemplary values in an example embodiment.

Figure 10 is a graph showing coupling efficiency for different θ_1 and θ_2 values in an example embodiment.

Figure 11 is a schematic flowchart illustrating a method of coupling light into or out of a planar waveguide structure in an example embodiment.

Figure 12 is a schematic flowchart illustrating a method of forming a planar waveguide structure in an example embodiment.

Figure 13 is a schematic flow diagram illustrating fabrication of a planar waveguide structure in an example embodiment.

Figure 14 is a schematic flowchart illustrating a method of coupling light out of a planar waveguide structure in an example embodiment.

DETAILED DESCRIPTION

Figure 1 is a schematic diagram illustrating a light coupling device/waveguide structure in an example embodiment. The device 100 comprises an array of light reflective structures such as a microprism array 102, 114 disposed in a first medium e.g. a cladding layer 104. The device 100 further comprises a textured surface structure 106 disposed in a second medium e.g. a guiding/core layer 108. The core layer is also referred to as a waveguide in the description. In the example embodiment, a light emitting element 110 is positioned adjacent the microprism array 102 that is associated with the textured surface structure 106. A light receiving element 112 is positioned adjacent a second microprism array 114 that is associated with a second textured surface structure 116. In the example embodiment, the microprism arrays 102, 114 and textured surface structures 106, 116 are made up of an air gap or a material with a lower refractive index than the refractive index of the

respective medium the arrays/textured surface structures are disposed in. A thin additional cladding layer (not shown) may be provided between the cladding layer 104 (including the microprism arrays 102, 114) and the waveguide 108.

5 Figure 2 is a detailed view of box 118 of Figure 1. In the example embodiment, light is coupled from a light source 110 to an optical waveguide (the guiding layer 108). Two arrays of light reflective structures (e.g. the microprism array 102 and the textured surface structure 106) comprise arrays of reflective planes 202, 204 respectively disposed at angles to the plane 206 of the optical waveguide 108.

10 The angles for the reflective planes 202, 204 in the example embodiment preferably satisfy a number of constraints to meet a wave propagation condition and for achieving an optimum reflection efficiency.

 In the description herein, although the light is described as being coupled
15 between the microprism array 102 and its associated textured surface structure 106 (i.e. coupling of light from the light emitting element 110 into the waveguide 108), it will be appreciated that the same principles apply for coupling light between the second microprism array 114 and the associated second textured surface structure 116 (i.e. coupling of light from the waveguide 108 into the light receiving element
20 112).

 In the example embodiment, an optimised-sized microprism array 102 can enhance light coupling efficiency into the waveguide/guiding layer 108 without using precise alignment operations with the textured surface structure 106. In the example
25 embodiment, incident light 208 is reflected at the microprism array 102 in the cladding layer 104 such that the light is refracted and coupled (see numeral 210) into the core layer 108. The light is reflected at the textured surface structure 106 (see numeral 212) of the core layer 108. The light is reflected (see numeral 214) at the interface 216 between the cladding layer 104 and the core layer 108. It will be appreciated that the
30 textured surface structure 106 can be in the form of, but not limited to, a micromirror array to facilitate light reflection. In the example embodiment, an array of microprism is used instead of a single prism or single mirror so that prior alignment with a light emitting source or a light receiving element is advantageously not needed.

Thus, the above example embodiment can provide a structure, and a method of designing such a structure, that can improve light coupling efficiency between a light source and an optical waveguide and/or a light-receiving element.

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Figure 3 is a schematic diagram illustrating light reflection in a first medium 302 in an example embodiment. The first medium 302 corresponds to the cladding layer 104 in Figures 1 and 2. An array of first reflective structures 304, 306 are constructed in the first medium 302. The first reflective structures 304, 306 are
 10 triangular in shape. For example, the structure 304 has an angle θ_1 , height h_1 , length L_1 , and spacing W_1 to the structure 306 for light passage into a second medium 307. The second medium 307 corresponds to the core layer 108 in Figures 1 and 2.

In the example embodiment, an incident light (shown schematically at 308)
 15 emitted from a light source (compare 110 of Figure 1) having an incident angle θ_i , 310 is reflected at an oblique side 312 of the triangle of the reflective structure 304. The angle between the other oblique side 314 and the interface 316 between the first medium 302 and the second medium 307 can be more than about 90 degrees. Such a triangular shape can provide ease of production e.g. using a manufacturing process utilising a
 20 mold. In general, using a mold, a bigger apex angle is easier to press and remove. However, it will be appreciated that a bigger apex angle translates into a longer L_1 , and the L_1 area blocks the light passage into a second medium 307.

In the example embodiment, the ratio of reflected incident light (A) 318 to total
 25 incident light (A+B) 318,320 is calculated as follows:

$$A = \frac{h_1}{\tan \theta_1} + h_1 \tan \theta_i \quad (1)$$

$$A + B = W_1 + L_1 \quad (2)$$

$$\frac{A}{A+B} = \frac{(h_1/\tan \theta_1) + h_1 \tan \theta_i}{W_1 + L_1} \quad (3)$$

It will be appreciated that the reflected light A 318 may be interrupted by the adjacent reflective structure 306 (see numeral 322). The ratio of non-interrupted reflected light (C) 324 to total reflected light (C+D) 324, 326 is calculated as follows:

$$C : C + D = W_1 : W_1 + L' \quad (4)$$

5 where L' is the length of structure 306 that interrupts the reflected light,

$$L' = \left(\frac{h_1}{\tan(2\theta_1 - \theta_i - 90)} \right) - W_1 - \frac{h_1}{\tan \theta_1} \quad (5)$$

$$\begin{aligned} \frac{C}{C+D} &= \frac{W_1}{W_1 + L'} \\ &= \frac{W_1}{\left(\frac{h_1}{\tan(2\theta_1 - \theta_i - 90)} \right) - h_1 / \tan \theta_1} \end{aligned} \quad (6)$$

10 Therefore, the ratio between the incident light (A+B) 318,320 and the light going through uninterrupted to the second medium 307 is calculated using equations (3) and (6) as follows:

$$\begin{aligned} \frac{A}{A+B} \times \frac{C}{C+D} &= \frac{(h_1 / \tan \theta_1) + h_1 \tan \theta_i}{W_1 + L_1} \times \frac{W_1}{\left(\frac{h_1}{\tan(2\theta_1 - \theta_i - 90)} \right) - h_1 / \tan \theta_1} \\ &= \frac{W_1}{W_1 + L_1} \times \frac{(h_1 / \tan \theta_1) + h_1 \tan \theta_i}{\left(\frac{h_1}{\tan(2\theta_1 - \theta_i - 90)} \right) - h_1 / \tan \theta_1} \\ &= \frac{W_1}{W_1 + L_1} \times \frac{\tan \theta_1 \tan \theta_i + 1}{\left(\tan \theta_1 / \tan(2\theta_1 - \theta_i - 90) \right) - 1} \end{aligned} \quad (7)$$

15 The first part of equation (7) comprises W_1 and L_1 and is referred to as a "receptive window opening ratio" and the second part comprises θ_1 , θ_i and h_1 and is referred to as an "angular efficiency".

20 The non-interrupted reflected light having an incident angle $90 - (2\theta_1 - \theta_i - 90)$, which is equal to $180 - 2\theta_1 + \theta_i$, is refracted at the interface 316 between the first medium 302 and the second medium 307. The refraction angle θ_j 328 is derived from Snell's Law.

$$\theta_j = \sin^{-1} \left(\left(\frac{n_1}{n_2} \right) \sin(180 - 2\theta_1 + \theta_i) \right) \quad (8)$$

where n_1 is the refractive index of the first medium 302 and n_2 is the refractive index of the second medium 307. It will be appreciated that the refraction angle θ_j 328 is wavelength dependent because both refractive indices n_1 and n_2 typically have wavelength dispersion. In the example embodiment, the wavelength region for the light is visible light wavelength, such as from about 400 nm to about 800 nm.

Figure 4 is a schematic diagram illustrating light reflection in the second medium 307 in the example embodiment. The light introduced into the second medium 307 having the angle θ_j 328 is reflected by an array of second reflective structures 402, 404 constructed in the second medium 307. In the example embodiment, the array of second reflective structures 402, 404 is constructed at an interface 403 between the second medium 307 and a third medium 405. The second reflective structures 402, 404 are triangular in shape. For example, the structure 402 has an angle θ_2 with a first oblique side, height h_2 , and length L_2 . The structure 404 shows an angle θ_2' with a second oblique side. In the following description, the structures 404, 406 are discussed interchangeably with the physical and angular characteristics.

The ratio of the light being reflected by an effective reflective plane (E) 406 of the reflective structure 404 to all of light introduced into the second medium 307 and contacting the structure 404, i.e. (E+F) 406, 408 is calculated as follows:

$$E = \left(\frac{h_2}{\tan \theta_2} \right) - h_2 \tan \theta_j \quad (9)$$

$$\begin{aligned} E + F &= L_2 \\ &= \frac{h_2}{\tan \theta_2} + \frac{h_2}{\tan \theta_2'} \end{aligned} \quad (10)$$

$$\frac{E}{E + F} = \frac{\frac{1}{\tan \theta_2} - \tan \theta_j}{\frac{1}{\tan \theta_2} + \frac{1}{\tan \theta_2'}} \quad (11)$$

The light entering the second medium 307 (shown schematically at 410) reflects at a reflective plane 412 and has an incident angle $\theta_2 + \theta_j$. The light may be interrupted by the adjacent reflective structure 404. The angle θ_k 414 is between the incoming light 410 and the reflective plane/surface 412.

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The angle α 416 is between reflected light 418 and the oblique side 420 of the adjacent triangle structure 404. The ratio of non-interrupted light (G) 422 to all light (G+H) 422, 424 reflected by the effective reflective plane 412 is calculated as follows:

$$G + H = \frac{h_2}{\sin \theta_2} \quad (12)$$

10

Also, the relationship among α , θ_k , θ_2 , θ_2' can be shown as follows by considering angle theorem around the interface 316 and the formed triangle comprising the three sides which are the reflective surface 412, the reflected light line 418 and the oblique side 420 of the adjacent triangle structure 404

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$$\begin{aligned} \alpha + \theta_k - \theta_2 &= \theta_2' \\ \alpha &= \theta_2 + \theta_2' - \theta_k \end{aligned} \quad (13)$$

$$\begin{aligned} H &= \left(\frac{h_2}{\sin \theta_2'} \right) \times \sin \alpha \times \frac{1}{\sin \theta_k} \\ &= \frac{h_2 \sin(\theta_2 + \theta_2' - \theta_k)}{\sin \theta_2' \sin \theta_k} \end{aligned} \quad (14)$$

Thus, the ratio of non-interrupted light (G) 422 to all light (G+H) 422, 424 reflected by the effective reflective plane 412 is

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$$\frac{G}{G + H} = 1 - \frac{\sin \theta_2 \sin(\theta_2 + \theta_2' - \theta_k)}{\sin \theta_2' \sin \theta_k} \quad (15)$$

Using equations (11) and (15), the ratio of the incident light to the reflective structure 402 in the second medium 307 to the non-interrupted light being reflected by the effective reflective plane 412 is calculated as follows:

25

$$\begin{aligned}
\frac{E}{E+F} \times \frac{G}{G+H} &= \frac{1/\tan \theta_2 - \tan \theta_j}{1/\tan \theta_2 + 1/\tan \theta'_2} \times \left(1 - \frac{\sin \theta_2 \sin(\theta_2 + \theta'_2 - \theta_k)}{\sin \theta'_2 \sin \theta_k} \right) \\
&= \frac{1 - \tan \theta_2 \tan \theta_j}{1 + \frac{\tan \theta_2}{\tan \theta'_2}} \times \left(1 - \frac{\sin \theta_2 \sin(\theta_2 + \theta'_2 - \theta_k)}{\sin \theta'_2 \sin \theta_k} \right)
\end{aligned} \tag{16}$$

The first part of equation (16) is referred to as “the ratio of effective reflective area” and the second part is referred to as “the structural efficiency”. Also, it will be appreciated that the equation (16) is wavelength dependent because it contains θ_j as a parameter, θ_j being wavelength dependent.

In order to maximize the structural efficiency, the angle α , which is equal to $\theta_2 + \theta'_2 - \theta_k$ under equation (13), preferably satisfies the following condition, which means that all the reflected light of structure 402 is not interrupted by the oblique side 420 of adjacent triangle/structure 404.

$$\begin{aligned}
\alpha &\leq 0 \\
\theta_2 + \theta'_2 - \theta_k &\leq 0 \\
\theta_k - \theta'_2 &\geq \theta_2
\end{aligned} \tag{17}$$

where,

$$\begin{aligned}
\theta_j + \theta_k + \theta_2 &= 90 \\
\theta_k &= 90 - \theta_j - \theta_2
\end{aligned} \tag{18}$$

Figure 5 shows internal reflection of light 502 at the interface 316 between the first medium 302 and second medium 307. The relationship in equation (18) is shown in Figure 5.

Further to the above, the second term of equation (16), such as $G/(G+H)$, can be omitted using this condition since all the reflected light under the condition can transmit to the interface 316 between the first medium 302 and the second medium 307.

Therefore, the condition for α can be rewritten in terms of θ_2 using equations (17) and (18) as follows:

$$90 - \theta_j - \theta'_2 \geq 2\theta_2 \quad (19)$$

5 By using equation (10), an equation (20) for θ'_2 can be obtained as follows:

$$L_2 = h_2 / \tan \theta_2 + h_2 / \tan \theta'_2$$

$$\theta'_2 = \tan^{-1} \left(\frac{1}{L_2 / h_2 - 1 / \tan \theta_2} \right) \quad (20)$$

By using the equation (8) for θ_j , equation (19) in terms of θ_2 is derived as follows:

$$10 \quad 90 - \sin^{-1} \left(\left(\frac{n_1}{n_2} \right) \sin(180 - 2\theta_1 + \theta_i) \right) - \tan^{-1} \left(\frac{1}{L_2 / h_2 - 1 / \tan \theta_2} \right) \geq 2\theta_2 \quad (21)$$

For the purposes of description, equation (21) is also referred to as constraint 1.

In the example embodiment, the reflected light by the second reflective structure 402, having an incident angle $2\theta_2 + \theta_j$ to the interface 316 between the second medium 307 and the first medium 302 preferably satisfies a total internal reflection condition, i.e. $2\theta_2 + \theta_j \geq \theta_c$.

To derive the condition, let θ_c be the critical angle at the interface 316 between the second medium 307 and the first medium 302.

$$20 \quad \theta_c = \sin^{-1} \left(\frac{n_1}{n_2} \right) \quad (22)$$

From Figure 5, for total internal reflection to occur,

$$90 - (\theta_k - \theta_2) \geq \theta_c \quad (23)$$

From equation 18, $\theta_k = 90 - \theta_j - \theta_2$

5 Therefore, using equations (18) and (23),

$$2\theta_2 + \theta_j \geq \theta_c \quad (24)$$

Therefore, using equations (8) and (22), another condition for the angle θ_2 is derived as follows:

$$10 \quad 2\theta_2 \geq \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right) \sin(180 - 2\theta_1 + \theta_i)\right) \quad (25)$$

For the purposes of description, equation (25) is also referred to as constraint 2.

Figure 6 is a graph for constraints 1 and 2 in an example embodiment. The graph is plotted using the following equations.

$$15 \quad 90 - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right) \sin(180 - 2\theta_1 + \theta_i)\right) - \tan^{-1}\left(\frac{1}{\frac{L_2}{h_2} - \frac{1}{\tan \theta_2}}\right) = 2\theta_2 \quad (26)$$

$$20 \quad 2\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right) \sin(180 - 2\theta_1 + \theta_i)\right) \quad (27)$$

25 The area 602 confined by the two constraints in the θ_1 - θ_2 space is available for designing the light coupling device in the example embodiment. It will be appreciated that the equations (26) and (27) and therefore, the area 602 are wavelength dependent because both refractive indices n_1 and n_2 in the equations (26) and (27) have wavelength dispersion.

30 Apart from identifying the two constraints for the design, size effects of the first and second reflective structures e.g. 304, 306 (Figure 3) and 402, 404 (Figure 4) are also described. It has been recognised that reflected light by the first reflective structures e.g. 304, 306 (Figure 3) may have diverging angles due to a diffraction effect of the reflective structures' edges or size.

Figure 7(a) is a graph showing beam width and beam distance results as a base size of the first reflective structure varies in an example embodiment. Using $\theta_i = 0$, $\theta_1 = 60$, $n_1 = 1.5464$ ($\lambda = 532\text{nm}$) where λ is the wavelength of a light source used, $n_2 = 1.6024$ ($\lambda = 532\text{nm}$), and $n_{R1} = 1.0$ (air) where n_{R1} is the refractive index of a first reflective structure, the relationship between the beam distance from the reflective structure and the reflected light beam width ($1/e$) for different L_1 is calculated by numerical simulation. Results are shown in Figure 7(a). Plot 702 shows the results for L_1 at about $1\text{ }\mu\text{m}$, plot 704 shows the results for L_1 at about $2\text{ }\mu\text{m}$, plot 706 shows the results for L_1 at about $3\text{ }\mu\text{m}$ and plot 708 shows the results for L_1 at about $4\text{ }\mu\text{m}$.

Using the above values and with a waveguide thickness of $50\text{ }\mu\text{m}$, the reflected light at a first reflective structure e.g. 304, 306 (Figure 3) reaches a second reflective structure e.g. 402, 404 (Figure 4) when the distance between two reflected points is about $90\text{ }\mu\text{m}$. In addition, a repetition period of the first reflective structure is $3 \times L_1$, i.e. W_1 equals to $2 \times L_1$.

By comparing the beam width at $90\text{ }\mu\text{m}$ distance (see numeral 710) in Figure 7, it is recognised that a smaller L_1 can advantageously lead to a bigger beam width. This is because each reflected light from a smaller first reflective structure desirably overlaps more, and the intensity of incident light reflected to a second reflective structure is thus more uniform. If intensity is more uniform, it can be beneficial/advantageous for manufacturing as an alignment process of the two layers of first and second reflective structures can be omitted.

Figure 7(b) is a graph showing reflection efficiency as a base size of the first reflective structure varies in an example embodiment. The parameters used are substantially identical to the conditions for obtaining Figure 7(a). It can be observed that reflection efficiency increases as the base size L_1 increases. For example, at numeral 712, the efficiency is about 26% for L_1 at about $1\text{ }\mu\text{m}$ while at numeral 714, the efficiency is about 33% for L_1 at about $4\text{ }\mu\text{m}$.

In view of the trends observed from Figures 7(a) and (b), the size of the first reflective structures e.g. 304, 306 (Figure 3), in terms of L_1 , is preferably in a range of about 2 μm to about 20 μm , more preferably in a range of about 4 μm to about 10 μm .

5 Figure 8(a) is a graph showing reflection efficiency and relative shift results as the base size of the second reflective structure varies in an example embodiment. Relative shift refers to a ratio of a shifted distance to the base size of the second reflective structure. For example, given a base size of 6 μm for the second reflective structure and the second reflective structure is shifted 3 μm from its initial position, the
 10 relative shift is 0.5. In the example embodiment, the first reflective structure is stationary. Using $\theta_i = 0$, $\theta_1 = 60$, $n_1 = 1.5464$ ($\lambda = 532\text{nm}$) where λ is the wavelength of a light source used, $n_2 = 1.6024$ ($\lambda = 532\text{nm}$), $n_{R1} = 1.0$ (air) where n_{R1} is the refractive index of the first reflective structure, $n_{R2} = 1.0$ (air) where n_{R2} is the refractive index of the second reflective structure, $L_1 = 1 \mu\text{m}$, and $\theta_2 = \theta_2' = 10$, and the waveguide thickness is taken as about 50
 15 μm , the relationship between the reflection efficiency of the second reflective structure and the relative shift for different sizes of L_2 is calculated by a numerical simulation. Results are shown in Figure 8(a). Plot 802 shows the results for L_2 at about 5 μm , plot 804 shows the results for L_2 at about 4 μm , plot 806 shows the results for L_2 at about 6 μm , plot 808 shows the results for L_2 at about 3 μm , plot 810 shows the results for L_2 at
 20 about 2 μm and plot 812 shows the results for L_2 at about 1 μm .

Using the above values, it is recognised that the reflection efficiency of the second reflective structure fluctuates when the size, L_2 , becomes larger. The average efficiency for L_2 at about 4 μm , about 5 μm and about 6 μm (see numerals 804, 802, 806
 25 respectively) shows similar values with periodicity in relation to relative shift. The efficiency for L_2 at about 1 μm , about 2 μm and about 3 μm (see numerals 812, 810, 808 respectively) appear constant at each relative shift. This may indicate that there is less 'reflection effect' when the L_2 is less than about 3 μm .

30 Figure 8(b) is a graph showing coupling efficiency results as the base size of a second reflective structure varies in an example embodiment. The parameters used are substantially identical to the conditions for obtaining Figure 8(a). Plot 814 shows the

coupling efficiency results for L_1 at about $1\ \mu\text{m}$ as the base size of the second reflective structure L_2 varies, plot 816 shows the results for L_1 at about $2\ \mu\text{m}$ as L_2 varies, plot 818 shows the results for L_1 at about $3\ \mu\text{m}$ as L_2 varies, plot 820 shows the results for L_1 at about $4\ \mu\text{m}$ as L_2 varies. It can be observed that the coupling efficiency shows an increasing trend as L_2 increases.

In view of the trends observed from Figures 8(a) and (b), the size of the second reflective structures e.g. 402, 404 (Figure 4), in terms of L_2 , is preferably from about $4\ \mu\text{m}$ to about $200\ \mu\text{m}$, more preferably about $10\ \mu\text{m}$ to about $50\ \mu\text{m}$. Preferably, during implementation, the L_2 size is larger than the L_1 size selected.

Thus, based on the above size analysis, by combining the first and second reflective structures having the sizes investigated, the light from a light source with a large area can advantageously be coupled into a planar optical waveguide effectively with reduced or no alignment constraint.

In an example implementation, using $\theta_i = 0$, $\theta_2 = \theta_2'$, $n_1 = 1.5464$ ($\lambda = 532\text{nm}$), $n_2 = 1.6024$ ($\lambda = 532\text{nm}$), $n_{R1} = 1.0$ (air), and $n_{R2} = 1.0$ (air), the available conditions for light coupling can be determined.

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Figure 9 is a graph showing constraints 1 and 2 of equations (21) and (25) plotted using the above values in an example embodiment. Plot 902 shows the results for constraint 1 (compare equation (21)) and plot 904 shows the results for constraint 2 (compare equation (25)). The area 906 is shows the range of available θ_1 and θ_2 values available in the above environment.

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Thus, for different θ_1 and θ_2 , there is an available range to satisfy the above values of reflective indices. The light coupling efficiency is calculated from,

$$\frac{A}{A+B} \times \frac{C}{C+D} \times \frac{E}{E+F} \quad (28)$$

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that is, a product of equations (7) and (11). This assumes that there is no reflection loss at the interface between the first medium having n_1 and the second medium having n_2 . It

is assumed that all reflected light by a second reflective structure is not interrupted by an adjacent reflective structure in the same medium. Thus, $H=0$ and therefore, $G/(G+H)=1$ and can be omitted from equation (28).

5 Figure 10 is a graph showing coupling efficiency for different θ_1 and θ_2 values in an example embodiment. The parameters used are substantially identical to the conditions for obtaining Figure 9. In the example embodiment, to obtain the coupling efficiency, equations (3) and (6) are considered separately to obtain the product in equation (7). It is assumed that $W/L_1=2$ and $L_2/L_1=2$. This is an example that all light
10 enters into the second medium (containing the second reflective structures), and is a different scenario from the drawing of Figure 3 in which some light hits or is interrupted by an adjacent reflective structure. Thus, Figures 9 and 10 simply depend on angles only. From Figure 10, at $\theta_1=60$ and $\theta_2=10$ degrees, the calculated coupling efficiency is about 12.2% (see numeral 1002).

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Figure 11 is a schematic flowchart 1100 illustrating a method of coupling light into or out of a planar waveguide structure in an example embodiment. At step 1102, an array of first light reflective structures formed in a first medium of the planar waveguide structure is used to reflect light into a second medium of the planar waveguide structure, each first light reflective structure having a first surface with a
20 first angle θ_1 relative to a longitudinal plane of the planar waveguide structure. At step 1104, an array of second light reflective structures formed in the second medium is used to propagate light via internal reflection in the second medium, each second light reflective structure having a second surface with a second angle θ_2
25 relative to the longitudinal plane of the planar waveguide structure. At step 1106, the second angle θ_2 and the first angle θ_1 are inter-related.

Figure 12 is a schematic flowchart 1200 illustrating a method of forming a planar waveguide structure in an example embodiment. At step 1202, an array of
30 first light reflective structures is formed in a first medium of the planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1

relative to a longitudinal plane of the planar waveguide structure for reflecting light into a second medium of the planar waveguide structure. At step 1204, an array of second light reflective structures is formed in the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure. At step 1206, the second angle θ_2 and the first angle θ_1 are inter-related for propagating light via internal reflection in the second medium.

Based on the above described example embodiments, two sets of reflectors each comprising an array of light reflective structures fabricated by for example, but not limited to, stamping, molding or embossing can be provided. The angles for the reflective structures preferably satisfy a region defined by two derived constraints to satisfy a wave propagation condition and to achieve an optimum reflection efficiency. It has been recognized that a light source or a photodetector placed on a waveguide directly for light propagation by reflection can improve the light coupling efficiency. Thus, a method and structure for coupling light from a light emitter into an optical waveguide and for coupling light from the waveguide to a light receiver can be provided.

Using the above described example embodiments, two layers comprising a specific shaped microprism array and a waveguide having a textured surface structure can be produced by e.g. stamping, injection molding, hot embossing and UV embossing techniques. Preferably, a thicker multimode waveguide can be constructed with thickness in the range of about 50 μm to about 200 μm . Furthermore, as alignment of the two layers is reduced or not a constraint, the layer of irregular waveguide can advantageously be simply picked and placed on the first layer of specific shaped microprism array. Using the above described example embodiments, incident light can be designed such that it is reflected twice using two reflectors to effectively couple light into a waveguide. The two reflectors are a combination of the specific shape microprism array and the irregular waveguide.

Figure 13 is a schematic flow diagram illustrating fabrication of a planar waveguide structure in an example embodiment. At step (a), a silicon wafer 1302 with v-grooves formed thereon is provided. A polydimethylsiloxane (PDMS) mold

structure 1304 is formed using the silicon wafer 1302. At step (b), using the mold structure 1304 (shown flipped horizontally) with the silicon wafer 1302 removed, clad pre-polymer 1306 is poured onto the mold structure 1304. At step (c), by removing the mold structure 1304, a medium comprising first reflective structures e.g. 1308 is formed (shown flipped horizontal). At step (d), a thin cladding layer 1310 is covered over the first reflective structures e.g. 1308 using a lamination technique. At step (e), a stamper structure 1312 is formed. The stamper structure 1312 comprises protrusion structures e.g. 1314. At step (f), a waveguide core material layer 1316 is spun onto the laminated cladding layer 1310 of step (d). At step (g), the stamper structure 1312 is aligned and stamped onto the waveguide core material layer 1316 (see arrow 1318). The protrusions e.g. 1314 are transferred to the waveguide core material layer 1316 and the stamper structure 1312 is removed. At step (h), the planar waveguide structure 1320 is formed.

In the following description, a fabrication example for forming the planar waveguide structure of Figure 13 is provided. For forming a first reflective structure, a master structure is prepared. One example for making a first reflective structure is using a (100) Si wafer. A SiO₂ layer is formed by a thermal oxidation process at about 1100 °C. Alternatively, an oxidized Si wafer is available commercially. The SiO₂ surface is cleaned by using a standard cleaning process such as, but not limited to, CAROS, SC-1, and O₃. A positive photoresist, which has dry etching resistivity against fluorinated etching gas, is spun on the cleaned SiO₂ surface by a spin-coating method. The photoresist is then heated at about 100 °C for a pre-baking process. The pre-baked photoresist is then exposed by UV light through a photomask, which is designed in order to make desired line-and-space patterns, by using a mask-aligner. The exposed photoresist is then developed by a photoresist developer to dissolve the exposed area. The developed photoresist is then heated at about 150 °C for a post-baking process. The exposed SiO₂ layer is then removed by the dry etching process by using fluorinated etching gas, such as CF₄, and/or CHF₃. After this process, the Si surface is partially exposed with the designed pattern by the photomask. The etching gas is then changed to O₂ for an ashing process to remove the photoresist. The wafer is then cleaned by the CAROS process in order to remove the photoresist completely. The cleaned wafer is then treated by 1% HF solution for about 2 minutes to remove the thin oxidized layer, which is

formed through the ashing process and CAROS cleaning process, on the exposed Si surface. The wafer is then etched by 13% KOH solution at about 85 °C for about 40 min to form the v-shape groove. The wafer with v-groove is then etched by 1% HF solution for about 20 minutes in order to dissolve the patterned SiO₂ layer.

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The master structure prepared by the above process is then transferred to polydimethylsiloxane (PDMS) for preparing a mold structure. The surface of the Si wafer is then treated by dimethyloctadecylchlorosilane solution in order to enhance the mold release characteristics. The PDMS pre-polymer and the curing agent, such as Sylgard 184 (Dow Corning, Co., MI), are mixed with a ratio of 10 to 1. The well stirred mixture is then placed under a vacuum condition for the deairing for about 15 minutes. The pre-polymer mixture is then poured onto the Si wafer and cured for about 1 hour at about 65 °C followed by a further curing process for about 15 minutes at about 135 °C. The PDMS mold is then taken out from the Si master structure.

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The master structure prepared by the above process is then replicated by the PDMS mold prepared using the above method. The under clad pre-polymer, such as UV curable epoxy, is then poured onto the PDMS mold and cured by UV irradiation for about 10 min. The PDMS mold is then removed after the curing process. The reflective structure is then covered by a thin cladding layer, between about 10 and about 20 micrometer thickness, by using a lamination technique.

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For forming a second reflective structure, a stamper structure is prepared. One example for making a second reflective structure is using a grayscale photomask. Photoresist is spun on a quartz substrate by a spin-coating method. The thickness of the photoresist is designed in order to obtain a protrusion structure with desired depth and angle by considering the etching selectivity to the quartz. The photomask is designed by considering the photoresist sensitivity, such as the relationship between the UV dosage and residual photoresist thickness. The photoresist is then heated for a pre-baking process. The pre-baked photoresist is then exposed by UV light through the grayscale photomask by using a mask-aligner. The exposed photoresist is then developed by the photoresist developer to dissolve the exposed area. The developed photoresist is then heated for a post-baking process. The

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quartz substrate is then etched by using fluorinated etching gas, such as CF_4 and/or CHF_3 .

For the waveguide fabrication process, the waveguide core material is spun
5 on the laminated cladding layer. The waveguide core material is then heated at about
100 °C for a pre-baking process. The stamper structure is then aligned to the wafer and
the protrusion structure is transferred. The pre-baked waveguide core material is then
exposed by UV light through the photomask by using the mask-aligner. The exposed
waveguide core material is then developed by the developer to dissolve unexposed
10 areas. The developed waveguide core structure is then heated at about 150 °C for a
post-baking process.

Figure 14 is a schematic flowchart 1400 illustrating a method of coupling light
out of a planar waveguide structure in an example embodiment. At step 1402, an
15 array of first light reflective structures formed in a first medium of the planar
waveguide structure is used to reflect light propagating in the planar waveguide
structure out of the first medium into a second medium of the planar waveguide
structure, each first light reflective structure having a first surface with a first angle θ_1
relative to a longitudinal plane of the planar waveguide structure. At step 1404, an
20 array of second light reflective structures formed in the second medium is used to
reflect light out of the second medium, each second light reflective structure having a
second surface with a second angle θ_2 relative to the longitudinal plane of the planar
waveguide structure.

25 It will be appreciated by a person skilled in the art that numerous variations
and/or modifications may be made to the present invention as shown in the specific
embodiments without departing from the spirit or scope of the invention as broadly
described. The present embodiments are, therefore, to be considered in all respects to
be illustrative and not restrictive.

CLAIMS

1. A planar waveguide structure, the structure comprising,
an array of first light reflective structures formed in a first medium of the
5 planar waveguide structure, each first light reflective structure having a first surface
with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure
for reflecting light into a second medium of the planar waveguide structure;
an array of second light reflective structures formed in the second medium,
each second light reflective structure having a second surface with a second angle
10 θ_2 relative to the longitudinal plane of the planar waveguide structure;
wherein the second angle θ_2 and the first angle θ_1 are inter-related for
propagating light via internal reflection in the second medium.
2. The structure as claimed in claim 1, wherein the array of the second
15 light reflective structures is formed as a textured surface of the second medium.
3. The structure as claimed in claim 2, wherein the textured surface is
disposed at an interface between the second medium and a third medium of the
planar waveguide structure.
- 20 4. The structure as claimed in any one of claims 2 to 3, wherein the
textured surface comprises a micromirror array.
5. The structure as claimed in any one of claims 1 to 4, wherein the array
25 of first reflective structures is disposed at an interface between the first medium and
the second medium.
6. The structure as claimed in any one of claims 1 to 5, wherein a filler
medium of each first reflective structure has a lower refractive index than the first
30 medium.

7. The structure as claimed in claim 6, wherein the filler medium of each first reflective structure comprises air.

8. The structure as claimed in any one of claims 1 to 7, wherein a filler medium of each second reflective structure has a lower refractive index than the second medium.

9. The structure as claimed in claim 8, wherein the filler medium of each second reflective structure comprises air.

10. The structure as claimed in any one of claims 1 to 9, wherein θ_2 is based on a first constraint

$$90 - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right) - \tan^{-1}\left(\frac{1}{L_2/h_2 - 1/\tan\theta_2}\right) \geq 2\theta_2$$

where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

11. The structure as claimed in any one of claims 1 to 10, wherein θ_2 is based on a second constraint $2\theta_2 \geq \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right)\sin(180 - 2\theta_1 + \theta_i)\right)$

where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

12. The structure as claimed in any one of claims 1 to 11, wherein each first light reflective structure is formed with a base length of between about 2 μm to about 20 μm .

13. The structure as claimed in any one of claims 1 to 12, wherein each second light reflective structure is formed with a base length between a range of about 4 μm to about 200 μm .

14. The structure as claimed in any one of claims 1 to 13, wherein the second medium is formed as a waveguide with a thickness in a range of about 50 μm to about 200 μm .

15. A method of coupling light into or out of a planar waveguide structure, the method comprising,

using an array of first light reflective structures formed in a first medium of the planar waveguide structure to reflect light into a second medium of the planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure;

using an array of second light reflective structures formed in the second medium to propagate light via internal reflection in the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure; and

wherein the second angle θ_2 and the first angle θ_1 are inter-related.

16. The method as claimed in claim 15, wherein the array of the second light reflective structures is formed as a textured surface of the second medium.

17. The method as claimed in claim 16, wherein the textured surface is disposed at an interface between the second medium and a third medium of the planar waveguide structure.

18. The method as claimed in any one of claims 16 or 17, wherein the textured surface comprises a micromirror array.

19. The method as claimed in any one of claims 15 to 18, wherein the array of first reflective structures is disposed at an interface between the first medium and the second medium.

5 20. The method as claimed in any one of claims 15 to 19, wherein a filler medium of each first reflective structure has a lower refractive index than the first medium.

21. The method as claimed in claim 20, wherein the filler medium of each
10 first reflective structure comprises air.

22. The method as claimed in any one of claims 15 to 21, wherein a filler medium of each second reflective structure has a lower refractive index than the second medium.

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23. The method as claimed in claim 22, wherein the filler medium of each second reflective structure comprises air.

24. The method as claimed in any one of claims 15 to 23, wherein θ_2 is
20 based on a first constraint

$$90 - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right) \sin(180 - 2\theta_1 + \theta_i)\right) - \tan^{-1}\left(\frac{1}{\frac{L_2}{h_2} - \frac{1}{\tan \theta_2}}\right) \geq 2\theta_2$$

where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each
25 second light reflective structure.

25. The method as claimed in any one of claims 15 to 24, wherein θ_2 is based on a second constraint $2\theta_2 \geq \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right) \sin(180 - 2\theta_1 + \theta_i)\right)$

where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_1 is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

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26. The method as claimed in any one of claims 15 to 25, wherein each first light reflective structure is formed with a base length of between about 2 μm to about 20 μm .

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27. The method as claimed in any one of claims 15 to 26, wherein each second light reflective structure is formed with a base length between a range of about 4 μm to about 200 μm .

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28. The method as claimed in any one of claims 15 to 27, wherein the second medium is formed as a waveguide with a thickness in a range of about 50 μm to about 200 μm .

29. A method of forming a planar waveguide structure, the method comprising,

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forming an array of first light reflective structures in a first medium of the planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure for reflecting light into a second medium of the planar waveguide structure;

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forming an array of second light reflective structures in the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure;

wherein the second angle θ_2 and the first angle θ_1 are inter-related for propagating light via internal reflection in the second medium.

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30. The method as claimed in claim 29, comprising forming the array of the second light reflective structures as a textured surface of the second medium.

31. The method as claimed in claim 30, further comprising forming the textured surface at an interface between the second medium and a third medium of the planar waveguide structure.

5 32. The method as claimed in any one of claims 30 or 31, further comprising forming the textured surface comprising a micromirror array.

33. The method as claimed in any one of claims 29 to 32, comprising forming the array of first reflective structures at an interface between the first
10 medium and the second medium.

34. The method as claimed in any one of claims 29 to 33, wherein a filler medium of each first reflective structure has a lower refractive index than the first medium.
15

35. The method as claimed in claim 34, wherein the filler medium of each first reflective structure comprises air.

36. The method as claimed in any one of claims 29 to 35, wherein a filler medium of each second reflective structure has a lower refractive index than the
20 second medium.

37. The method as claimed in claim 36, wherein the filler medium of each second reflective structure comprises air.

25 38. The method as claimed in any one of claims 29 to 37, wherein θ_2 is based on a first constraint

$$90 - \sin^{-1} \left(\left(\frac{n_1}{n_2} \right) \sin(180 - 2\theta_1 + \theta_i) \right) - \tan^{-1} \left(\frac{1}{L_2/h_2 - 1/\tan \theta_2} \right) \geq 2\theta_2$$

30 where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a

length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

39. The method as claimed in any one of claims 29 to 38, wherein θ_2 is
 5 based on a second constraint $2\theta_2 \geq \sin^{-1}\left(\frac{n_1}{n_2}\right) - \sin^{-1}\left(\left(\frac{n_1}{n_2}\right) \sin(180 - 2\theta_1 + \theta_i)\right)$

where n_1 is the refractive index of the first medium, n_2 is the refractive index of the second medium, θ_i is a light incident angle for light incident on the first surface, L_2 is a length of a base of each second light reflective structure and h_2 is a height of each second light reflective structure.

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40. The method as claimed in any one of claims 29 to 39, further comprising forming the first light reflective structure with a base length of between about 2 μm to about 20 μm .

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41. The method as claimed in any one of claims 29 to 40, further comprising forming the second light reflective structure with a base length between a range of about 4 μm to about 200 μm .

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42. The method as claimed in any one of claims 29 to 41, further comprising forming the second medium as a waveguide with a thickness in a range of about 50 μm to about 200 μm .

43. A planar waveguide structure, the structure comprising,
 an array of first light reflective structures formed in a first medium of the
 25 planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1 relative to a longitudinal plane of the planar waveguide structure for reflecting light propagating in the planar waveguide structure out of the first medium into a second medium of the planar waveguide structure;
 an array of second light reflective structures formed in the second medium,
 30 each second light reflective structure having a second surface with a second angle

θ_2 relative to the longitudinal plane of the planar waveguide structure for reflecting light out of the second medium.

44. A method of coupling light out of a planar waveguide structure, the
5 method comprising,

using an array of first light reflective structures formed in a first medium of the planar waveguide structure to reflect light propagating in the planar waveguide structure out of the first medium into a second medium of the planar waveguide structure, each first light reflective structure having a first surface with a first angle θ_1
10 relative to a longitudinal plane of the planar waveguide structure;

using an array of second light reflective structures formed in the second medium to reflect light out of the second medium, each second light reflective structure having a second surface with a second angle θ_2 relative to the longitudinal plane of the planar waveguide structure.