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(54) Title: OPTICAL ENGINE

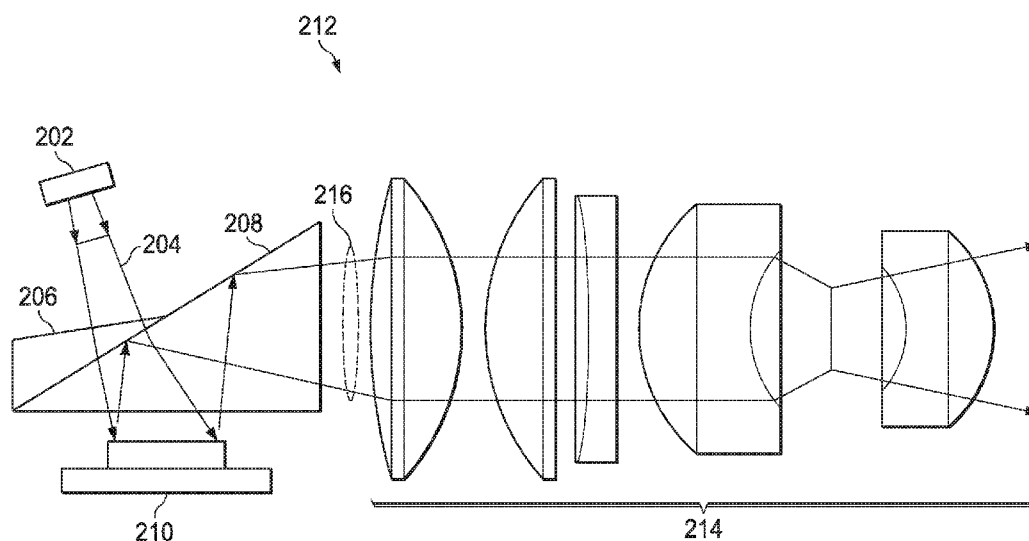


FIG. 2

(57) **Abstract:** Described examples include an optical device (212), having a light source (202) with a light source output and a light integrator (204) having a light integrator input and a light integrator output, the light integrator input optically coupled to the light source output, and the light integrator (204) configured to provide divergent light at the light integrator output responsive to the light at the light source output. The optical device (212) also has: projection optics (214) with an optics input and an optics output, the projection optics (214) configured to project output light at the optics output responsive to modulated light at the optics input, in which a focal point of the optics input matches a divergence of the modulated light; and a spatial light modulator (210) optically coupled between the light integrator output and the optics input. The spatial light modulator (210) is configured to provide the modulated light responsive to the divergent light.



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Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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OPTICAL ENGINE

[0001] This relates generally to optical engines, and more particularly to optical engines that may be applicable to three-dimensional printing.

BACKGROUND

[0002] Three-dimensional printing is useful in many fields, such as manufacturing and artistic design. The cost of three-dimensional printing is falling; thus, making more and more applications for this technology financially feasible. One type of three-dimensional printer is the photo-polymerization printer. This type of printer uses light to convert a liquid polymer to a solid. One type of photopolymerization printer is a vat type. This type of printer uses a vat with a transparent bottom to contain photo-polymerizable liquid. Initially, a lift plate is one layer from the bottom of the vat. Each printer has a layer thickness that the printer develops, which may be tens to hundreds of microns thick. An optical engine is below the vat. The optical engine uses light to expose a pattern for the initial layer derived from a three-dimensional electronic model of the object to be printed. The light causes the liquid in the vat to polymerize in that pattern and thus form solid material. The lift plate then rises a layer and then exposes the next layer of the object. This process repeats until the printer forms all layers of the object.

[0003] With photo-polymerization printers, the optical engine can produce layers with very high resolution. For example, a digital light processing (DLP) optical engine can produce patterns with millions of pixels. However, such optical engines can be relatively expensive. To be competitive, the cost of the optical engine in this type of device must be lowered while maintaining high resolution output.

SUMMARY

[0004] In accordance with an example, an optical device, includes a light source having a light source output, the light source configured to provide light at the light source output and a light integrator having a light integrator input and a light integrator output, the light integrator input optically coupled to the light source output, and the light integrator configured to provide divergent light at the light integrator output responsive to the light at the light source output. The optical device also includes projection optics having an optics input and an optics output, the

projection optics configured to project projection output light at the optics output responsive to modulated light at the optics input, in which a focal point of the optics input matches a divergence of the modulated light and a spatial light modulator optically coupled between the light integrator output and the optics input. The spatial light modulator is configured to provide the modulated light responsive to the divergent light..

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. 1 is a diagram of a three-dimensional printer.

[0006] FIG. 2 is a diagram of an example optical engine.

[0007] FIG. 3 is a diagram of a light integrator.

[0008] FIG. 4 is a diagram of an example light integrator.

[0009] FIGS. 5A through 5D (collectively "FIG. 5") are diagrams of an example light integrator.

[0010] FIGS. 6A and 6B (collectively "FIG. 6") are diagrams illustrating an example method for making an example light integrator.

[0011] FIG. 7 is a flow diagram of an example method.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0012] In the drawings, corresponding numerals and symbols generally refer to corresponding parts unless otherwise indicated. The drawings are not necessarily drawn to scale.

[0013] The term "coupled" is herein. The term "coupled" may include connections made with intervening elements, and additional elements and various connections may exist between any elements that are "coupled." Elements are referred to herein as "optically coupled" when a connection between the elements involves transmission or reception of light.

[0014] The term "matches" is used herein in reference to projection optics and to the divergence of modulated light. As used herein, a focal point of a projection optics "matches" the divergence of modulated light when the focal point of an input of the projection optics is approximately within $\pm 10\%$ (as measured by the distance from the input of the projection optics to the focal point of the input of the projection optics) of the focal point of the modulated light.

[0015] In example arrangements, the problem of providing a low cost, high quality optical engine is solved by using a light integrator to direct light from a light source to a spatial light modulator, which avoids the need for additional lenses between the light source and the spatial light modulator. In an example, an optical device, includes a light source having a light source

output, has the light source configured to provide light at the light source output. The optical device also includes a light integrator with a light integrator input and a light integrator output that has the light integrator input optically coupled to the light source output. The light integrator is configured to provide divergent light at the light integrator output responsive to the light at the light source output. The optical device also includes projection optics having an optics input and an optics output. The projection optics is configured to project projection output light at the optics output responsive to modulated light at the optics input. A focal point of the optics input matches a divergence of the modulated light and a spatial light modulator optically coupled between the light integrator output and the optics input. The spatial light modulator is configured to provide the modulated light responsive to the divergent light.

[0016] FIG. 1 is a diagram of a three-dimensional printer 100. Three-dimensional printer 100 prints a three-dimensional object layer-by-layer from an electronic model of the object. Vat 102 has a transparent bottom. Lift plate 104 is positioned in vat 102 by control arm 106. Vat 102 is filled with photo-polymerizing resin 108. Control arm 106 positions lift plate 104 a layer thickness 110 from the bottom of vat 102. In examples, the layer thickness is 0.05 to 0.15mm. When the lift plate is in position, optical engine 112 projects light in a pattern of the first layer of the object to be printed. Where light from the optical engine 112 strikes photo-polymerizing resin 108, photo-polymerizing resin polymerizes and forms solid material. Thus, the first layer of the object to be printed is formed.

[0017] The first layer adheres to lift plate 104. Lift plate 104 is then lifted by another layer thickness 110. In some examples, control arm 106 lifts, twists and/or tilts lift plate 104 to release the first layer from the bottom of vat 102. When the lift plate 104 is in position for the next layer of the object to be printed, optical engine 112 projects light in the pattern of the next layer of the object to be printed. This process repeats until all layers of the object are printed.

[0018] FIG. 2 is a diagram of an example optical engine 212. Optical engine 212 is like optical engine 112 (FIG. 1). Light source 202 is a light emitting diode (LED) in this example. In other examples, light source 202 is another source of light, such as a high intensity incandescent light. In this example, the LED produces 1255 mW of optical power. The wavelength of light produced by light source 202 is selected for efficient polymerizing photo-polymerizing resin 108 (FIG. 1). In this example, light source 202 produces light of approximately 405 nm. In other examples, light source 202 produces light in a range of 350 – 460 nm. In many light sources for

optical engines, light from the light source is collimated at the output of the light source. However, this requires additional lenses at the output of light source 202. In this example, the light integrator input of light integrator 204 is proximate to light source 202, and thus the light integrator input of light integrator 204 optically couples to light source 202. This captures as much light as possible without the need for collimating lenses. In addition, in this example, the form factor of the light integrator input of light integrator 204 is approximately the same as the form factor of the light source output of light source 202, which increases the portion of light from light source 202 that enters light integrator 204.

[0019] The light integrator output of light integrator 204 is larger than the light integrator input of light integrator 204. As explained further hereinbelow, this configuration lowers the spread of light from the light integrator output of light integrator 204 so that the light is efficiently provided to spatial light modulator 210. Light integrator 204 homogenizes the light from light source 202 by multiple reflections of the light inside light integrator 204. In addition, light integrator 204 helps direct as much light as possible onto spatial light modulator 210. As used herein, the term “light integrator” includes light tunnels, integrating rods, light pipes, and compound parabolic concentrators. Although other types of devices perform light integration, such as micro-lens arrays, these other types of devices are not included in the term “light integrator” as used herein. In this example, light integrator 204 is a light tunnel.

[0020] Divergent light from the light integrator output of light integrator 204 passes through cover prism 206. The divergent light from the light integrator output of light integrator 204 has a form that roughly matches the form factor of spatial light modulator 210. Cover prism 206 provides a surface that is perpendicular to the propagation path of the output of light integrator 204 to lower distortion of the form of light output from light integrator 204. In addition, the higher refractive index of cover prism 206 relative to air lowers the divergence of the light from the output of light integrator 204. The light then passes through an air gap (not shown) and through reverse total internal reflection prism (RTIR prism) 208. Thus, the light integrator output of light integrator 204 optically couples to spatial light modulator 210. In this example, spatial light modulator 210 is a digital micromirror device (DMD). Other examples use other spatial light modulators, such as liquid crystal on silicon (LCOS) modulators. With DMDs, each pixel is a movable mirror that modulates light by reflecting in an ON direction and an OFF direction, depending on the data for that pixel provided to the DMD. The angle of the surface of

RTIR prism 208 closest to light integrator 204 is such that it reflects ON direction light from pixels reflecting of spatial light modulator 210 but does not reflect light from light integrator 204. Therefore, the image for projection reflects from RTIR prism 208 to projection optics 214, and thus spatial light modulator 210 optically couples to the optical input of projection optics 214. As noted above, the light from light source 202 is not collimated before light integrator 204. As explained further hereinbelow regarding FIGS. 3 and 4, the light exiting light integrator 204 is divergent. The pixels of spatial light modulator 210 are mirrors, therefore modulated light 216 is also divergent as it enters the optical input of projection optics 214. Projection optics are often telecentric and thus are designed for non-divergent and non-convergent (i.e. collimated) light that has an infinite input focal distance. In this example, modulated light 216 is divergent, so projection optics 214 must have an input focal point directed to the point of divergence, and thus is non-telecentric. Because light integrator 204 modifies the divergence of the light from light source 202, the point of divergence or input focal point is calculated using the angle of divergence of the light at the output of light integrator 204. Therefore, the focal point of the optics input of projection optics 214 matches the divergence of modulated light 216. As used herein, a focal point of the projection optics 214 “matches” the divergence of the modulated light 216 when the focal point of the input of projection optics 214 is approximately within $\pm 10\%$ (as measured by the distance from the input of the projection optics 214 to the focal point of the input of the projection optics 214) of the focal point of the modulated light 216. In other words, the focal point of the projection optics 214 matches the modulated light 216 when the projection optics 214 approximately converts the divergent modulated light 216 to telecentric light. The optics output of projection optics 214 focuses on a target. That is, the focal point of the optics output of projection optics 214 is on the photo-polymerizing resin 108 (FIG. 1) between the lift plate 104 (FIG. 1) and the bottom of vat 102 (FIG. 1). In an example, projection optics 214 may include five lenses using N-BK7 glass. In this example, the five lenses are spherical. In an example, projection optics 204 has an f-number of 3.

[0021] FIG. 3 is a diagram of a light integrator 304 where the output face 306 has the same size as the input face 308. With a light source 302 in proximity to input face 308, the full spread angle α of the light output from light source 302 enters light integrator 304. In this configuration, light integrator 304 cannot be a light rod unless the light rod has mirror coated surfaces. This is because, the angle of reflection for the light from light source 302 is too great

for total internal reflection (TIR). Therefore, without reflective surfaces, too much of the output of light source 302 would pass through the walls of light integrator 304 and not propagate to output face 306. Because the walls of light integrator 304 are parallel to the propagation direction of the light, the output spread angle is also α .

[0022] FIG. 4 is a diagram of an example light integrator 404. Light integrator 404 is like light integrator 204 (FIG. 2). In this example, output face 406 is larger than input face 408. Light source 402 provides light having a spread of α . However, because the walls of light integrator 404 are not parallel to the propagation direction of the light, light from light source 402 reflects at a more oblique angle. Therefore, the output spread angle β is a smaller angle than α . This smaller angle lowers the divergence of the light from output face 406 and thus allows for provision of the light from light integrator 404 to a spatial light modulator like spatial light modulator 210 (FIG. 2) without redirection of the light by additional lenses. In addition, this configuration may allow for the use of TIR-based integrator rods because the angle of reflection of incoming light is more oblique. As used herein, the output of a light integrator like light integrator 404 is “divergent” when β is greater than 18° (i.e. the light diverges from the output light’s propagation path by greater than 9°).

[0023] FIGS. 5A through 5D (collectively “FIG. 5”) are diagrams of an example light integrator 504. Light integrator 504 is like light integrator 204 (FIG. 2). FIG. 5A is a side view of light integrator 504. FIG. 5B is a top view of light integrator 504. FIG. 5C is a view of the output of light integrator 504. The size and configuration shown in FIG. 5C is an output form factor for light integrator 504. FIG. 5D is a view of the input of light integrator 504. The size and configuration shown in FIG. 5D is an input form factor for the light integrator 504. As used herein, the terms “top” and “side” only indicate the relative position of views and do not indicate any other physical relationship. Light integrator 504 has a length L . The input of light integrator 504 has a height H_i and a width W_i . The output of light integrator has a height H_o and a width W_o . In an example, the input of light integrator 504 is square, thus $H_i = W_i$. In an example, the size and form factor of the input of light integrator 504 matches the size and form factor of the input light source, like light source 202 (FIG. 2), so that light integrator 504 captures the as much of the output of the light source as possible. Thus, if the output window of a light source, such as an LED, is a square that is 1mm on each side, H_i and W_i would be about 1mm, for example. In an example, L is about eight times the greater of H_i and W_i . Thus, if H_i is 1mm, L would be

8mm. However, in other examples, L is up to twenty times H_i or W_i .

[0024] H_o and W_o are selected to match the aspect ratio or form factor of the spatial light modulator to be illuminated, such as spatial light modulator 210 (FIG. 2). The size of these dimensions involves a trade-off. The greater these dimensions are relative to the dimensions of the input of light integrator 504, the less the output light diverges. However, greater dimensions affect the uniformity of the output light and reduces the efficiency of light integrator 504. Another important design consideration is fully illuminating the spatial light modulator. With this consideration, the output pattern of light integrator 504 should be greater than the size of the spatial light modulator so that the spatial light modulator is fully illuminated.

[0025] FIGS. 6A and 6B (collectively “FIG. 6”) are diagrams illustrating an example method for making an example light integrator 604. The dimensions of FIG. 6 are not to scale, but rather are selected for ease of illustration. FIG. 6A shows example light integrator as a single sheet including panel 612, panel 614, panel 616, panel 618, and panel 620. One side of each of the panels includes a mirrored surface, such as a layer of aluminum. In an example, the example light integrator 604 is a sheet of aluminum with a backing for structural integrity. The sheet is folded at an angle of 90° at the boundary between panels such that panels 612 and 620 fold onto each other. Thus, this example light integrator is easy to manufacture, and thus inexpensive.

[0026] FIG. 7 is a flow diagram of an example method 700. Step 702 is providing a source of light, such as light source 202 (FIG. 2). Step 704 is directing light from the source of light through a light integrator, such as light integrator 204 (FIG. 2), wherein the light integrator provides divergent output light to a spatial light modulator. Step 706 is reflecting the divergent output light off the spatial light modulator, such as spatial light modulator 210 (FIG. 2) to projection optics, such as projection optics 214 (FIG. 2), the projection optics having an input focal point corresponding to a divergence of the divergent output light and having an output focal point at a target.

[0027] Modifications are possible in the described examples, and other examples are possible, within the scope of the claims.

CLAIMS

What is claimed is:

1. An optical device, comprising:
 - a light source having a light source output, the light source configured to provide light at the light source output;
 - a light integrator having a light integrator input and a light integrator output, the light integrator input optically coupled to the light source output, and the light integrator configured to provide divergent light at the light integrator output responsive to the light at the light source output;
 - projection optics having an optics input and an optics output, the projection optics configured to project projection output light at the optics output responsive to a modulated light at the optics input, in which a focal point of the optics input matches a divergence of the modulated light; and
 - a spatial light modulator optically coupled between the light integrator output and the optics input, the spatial light modulator configured to provide the modulated light responsive to the divergent light.
2. The optical device of claim 1, wherein the light integrator input has an input form factor that matches a form factor of the light source output and the light source output is proximate to the light integrator input.
3. The optical device of claim 1, further comprising a reverse total internal reflection prism configured to pass the divergent light through a face of the reverse total internal reflection prism before reaching the spatial light modulator, and configured to reflect the modulated light off the face before entering the optics input of the projection optics.
4. The optical device of claim 3, further comprising a cover prism between the light integrator and the reverse total internal reflection prism, wherein the cover prism has a surface perpendicular to a propagation path of the divergent light.
5. The optical device of claim 1, wherein the light source is a light emitting diode.
6. The optical device of claim 1, wherein the light integrator is a light tunnel.
7. The optical device of claim 1, wherein the divergent light has a pattern corresponding to a form factor of the spatial light modulator.
8. The optical device of claim 1, wherein the projection optics includes five lenses.

9. A three-dimensional printer, comprising:
a vat having a transparent bottom and configured to contain a photo-polymerizing resin;
a lift plate movably positioned within the vat; and
an optical device configured to project a pattern of light through the transparent bottom,
the optical device further including:
a light source having a light source output, the light source configured to provide light at the light source output;
a light integrator having a light integrator input and a light integrator output, the light integrator input optically coupled to the light source output, and the light integrator configured to provide divergent light at the light integrator output responsive to the light at the light source output;
projection optics having an optics input and an optics output, the projection optics configured to project projection output light at the optics output through the transparent bottom responsive to a modulated light at the optics input, in which a focal point of the optics input matches a divergence of the modulated light; and
a spatial light modulator optically coupled between the light integrator output and the optics input, the spatial light modulator configured to provide the modulated light responsive to the divergent light.
10. The three-dimensional printer of claim 9, wherein the light integrator input has an input form factor that matches an output form factor of the light source output and the light source output is proximate to the light integrator input.
11. The three-dimensional printer of claim 9, wherein the lift plate is positioned and moved by a control arm.
12. The three-dimensional printer of claim 9, further comprising a reverse total internal reflection prism configured to pass the divergent light through a face of the reverse total internal reflection prism before reaching the spatial light modulator, and configured to reflect the modulated light off the face before entering the optics input of the projection optics.
13. The three-dimensional printer of claim 12, further comprising a cover prism between the light integrator and the reverse total internal reflection prism, wherein the cover prism has a surface perpendicular to a propagation path of the divergent light.
14. The three-dimensional printer of claim 9, wherein the light source is a light emitting

diode.

15. The three-dimensional printer of claim 9, wherein the light integrator is a light tunnel.

16. The three-dimensional printer of claim 9, wherein the divergent light has a pattern corresponding to a form factor of the spatial light modulator.

17. The three-dimensional printer of claim 9, wherein the projection optics includes five lenses.

18. A method, comprising:

directing light from a source of light through a light integrator, wherein the light integrator provides divergent output light to a spatial light modulator; and

reflecting the divergent output light off the spatial light modulator to projection optics, the projection optics having an input focal point corresponding to a divergence of the divergent output light and having an output focal point at a target.

19. The method of claim 18, wherein the projection optics receives the divergent output light reflected off the spatial light modulator via a reverse total internal reflection prism.

20. The method of claim 18, wherein the source of light is a light emitting diode.

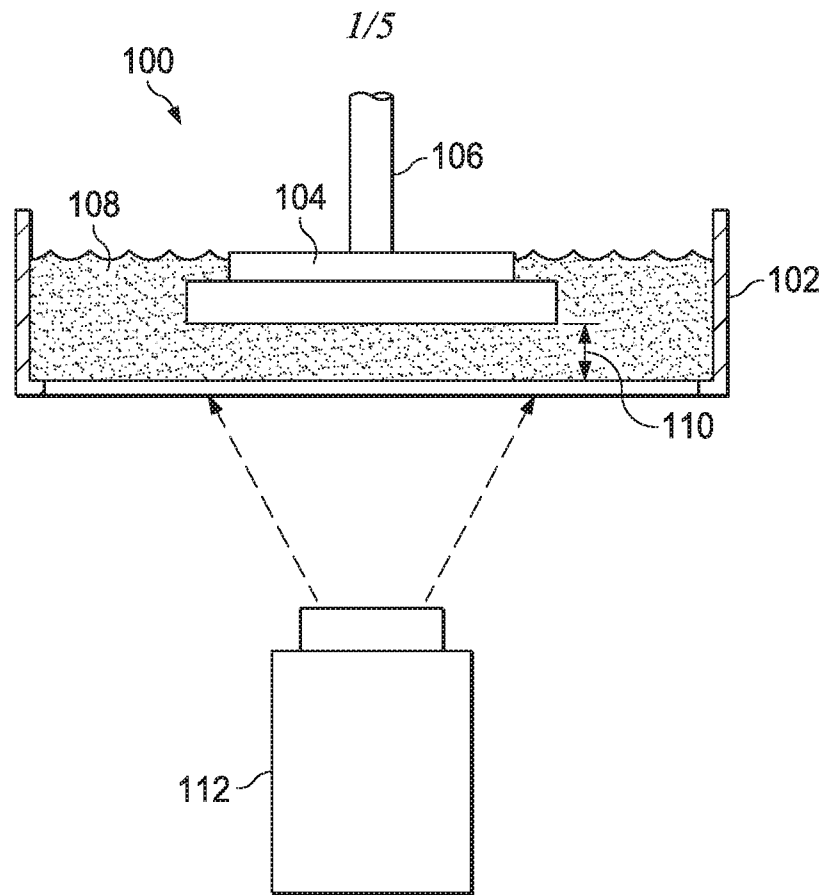


FIG. 1

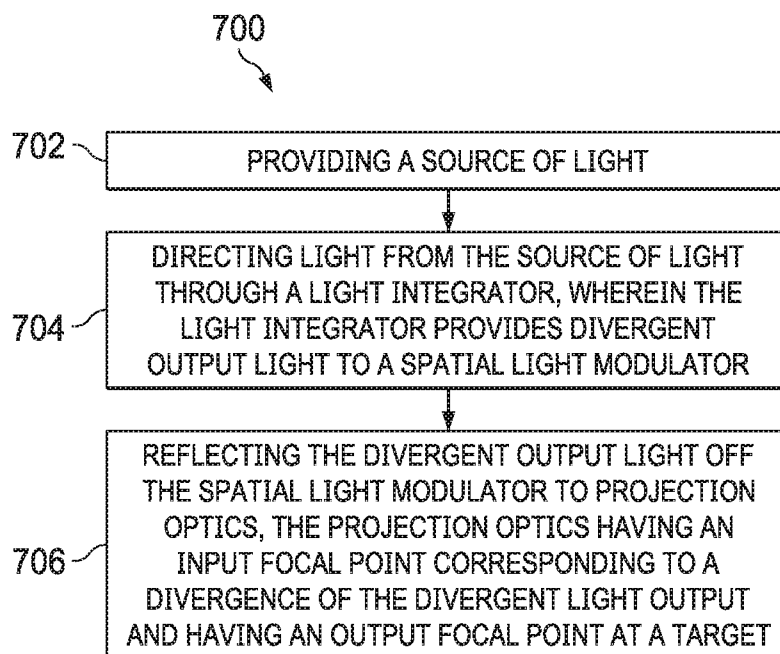


FIG. 7

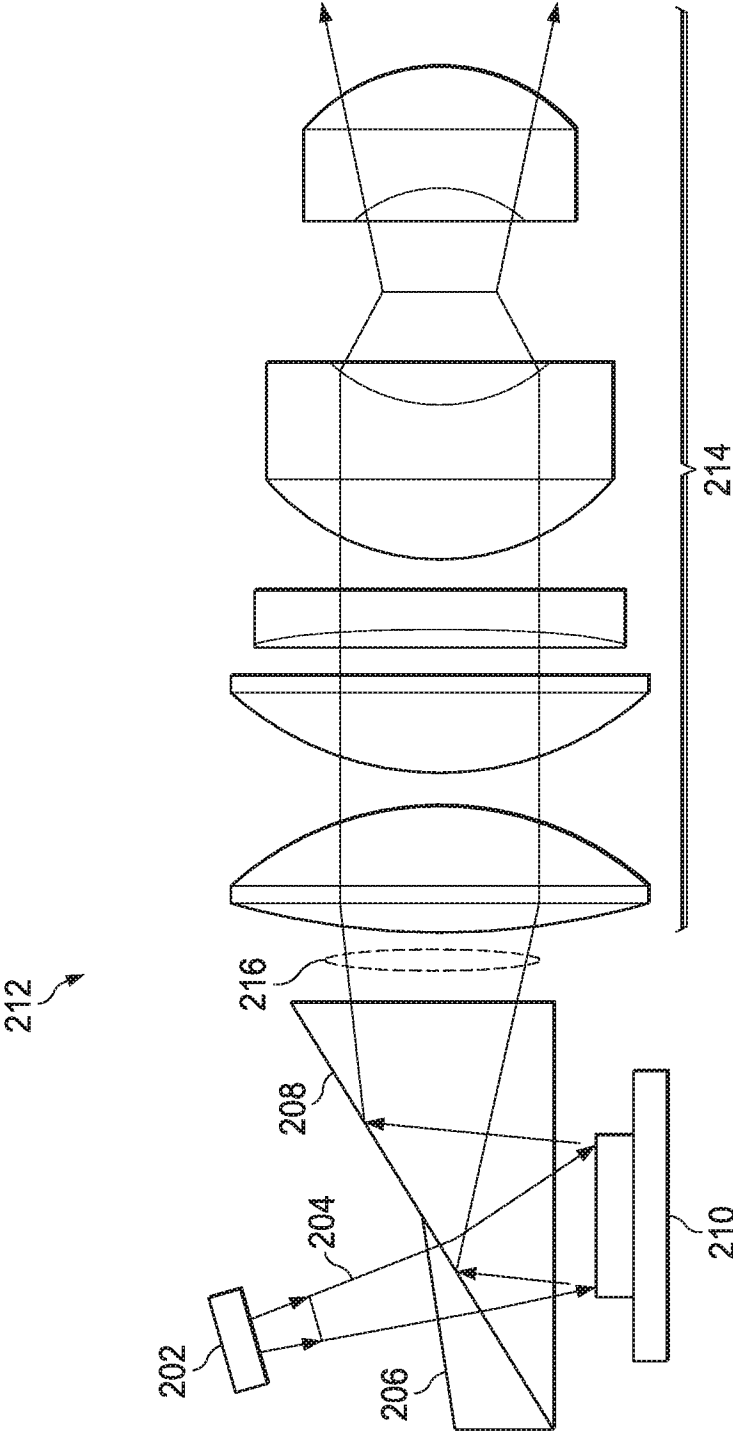
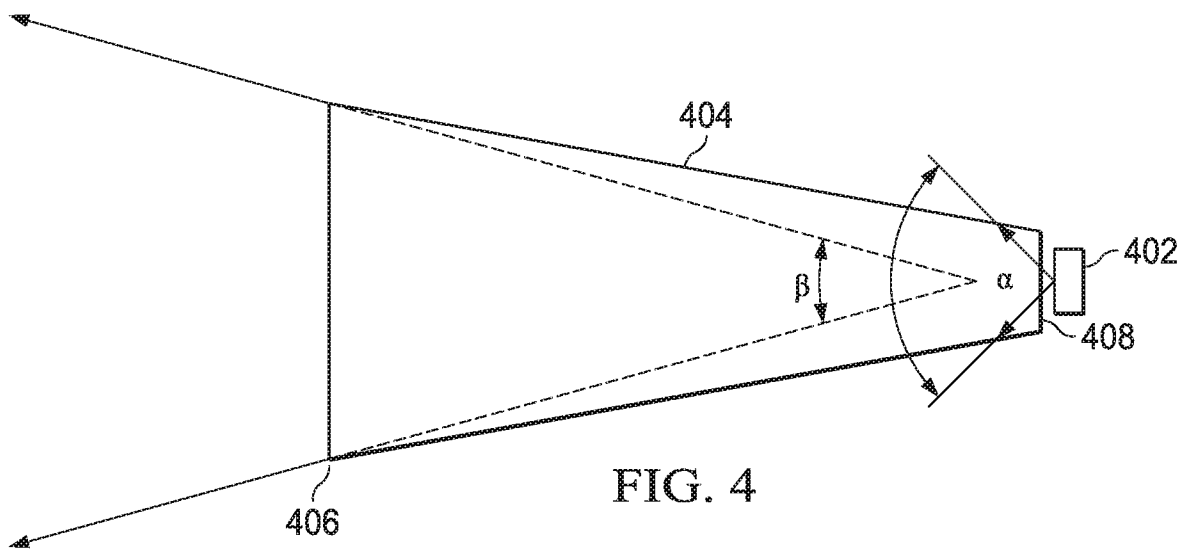
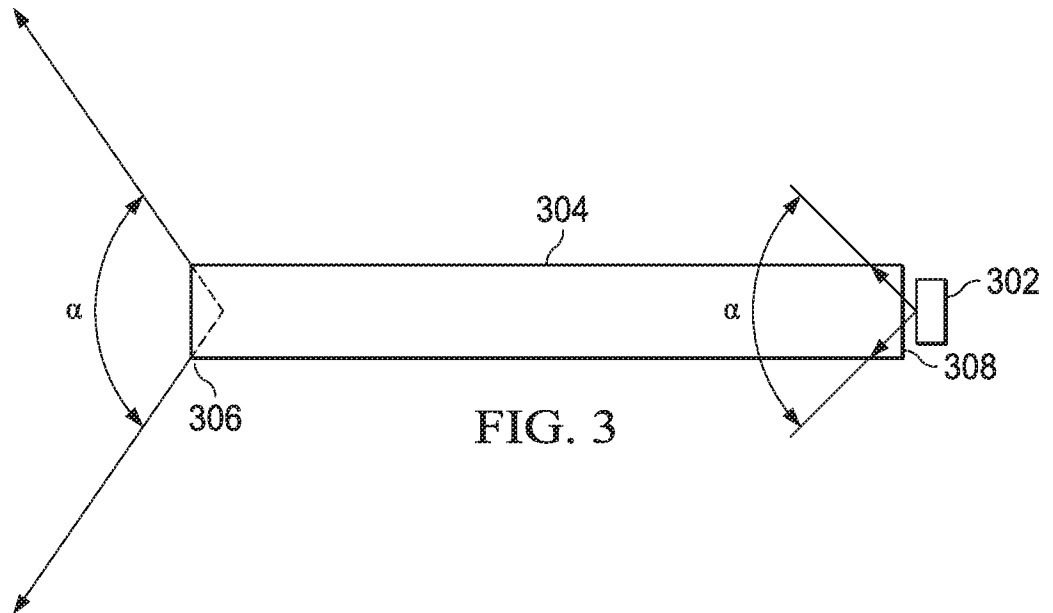
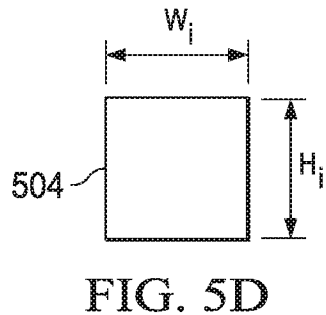
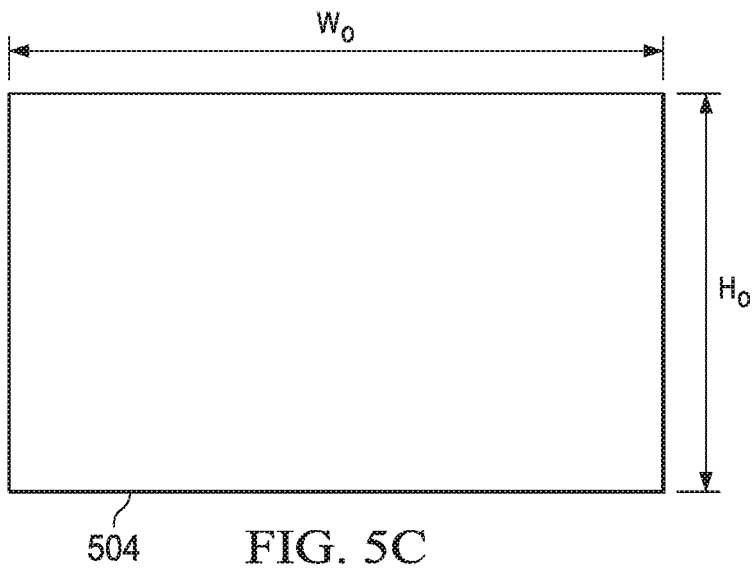
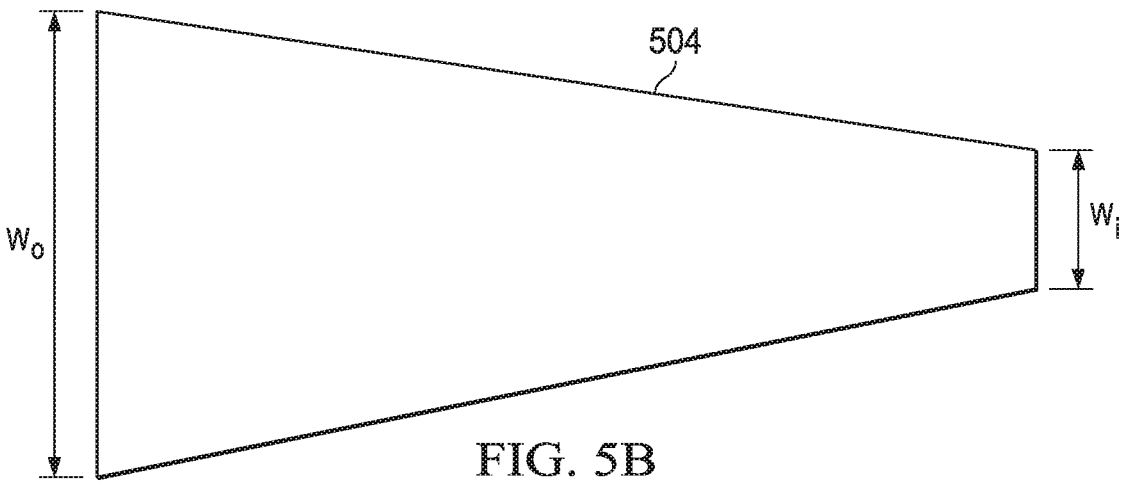
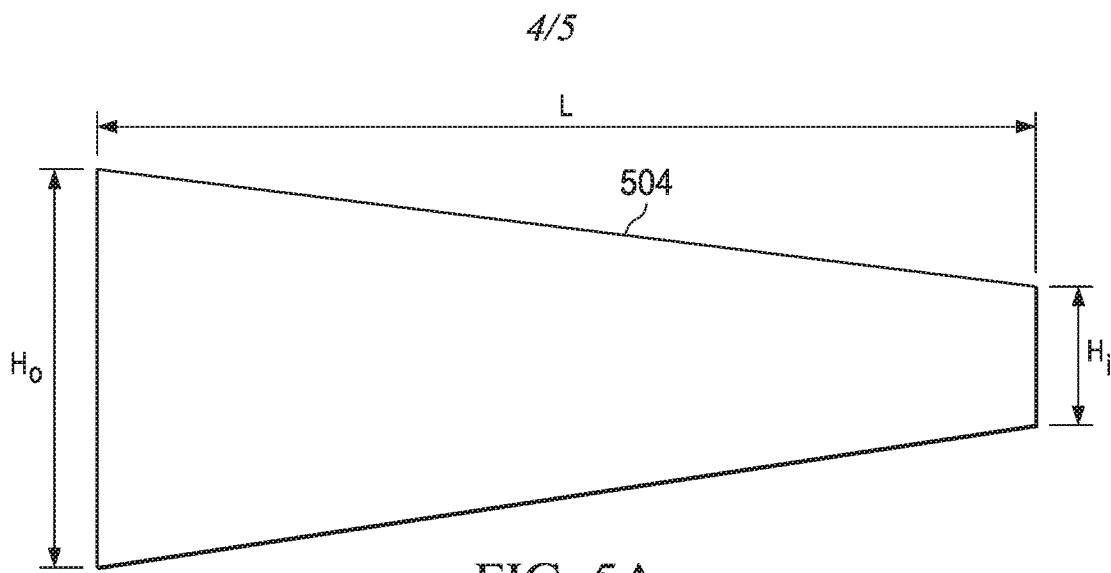


FIG. 2

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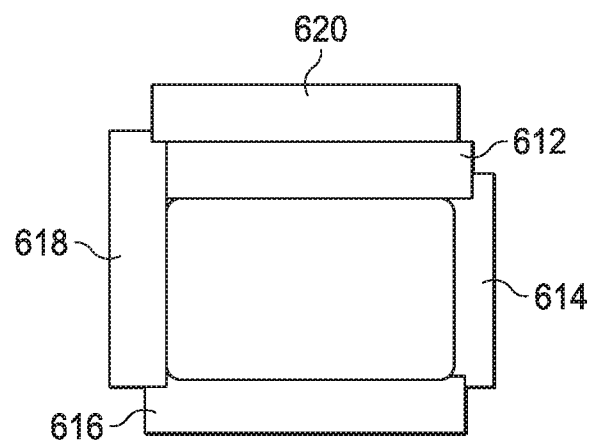
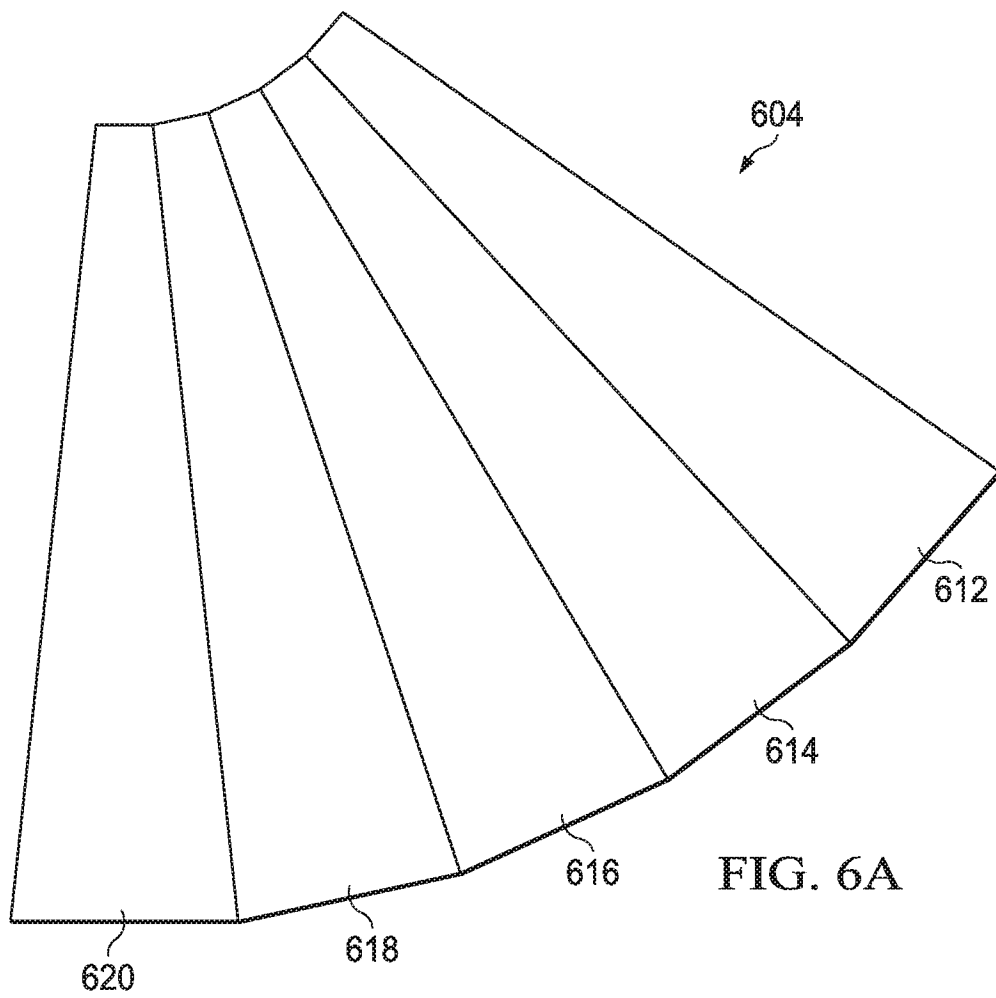


FIG. 6B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2019/043250

A. CLASSIFICATION OF SUBJECT MATTER

G02B 27/18 (2006.01)**B33Y 30/00 (2015.01)****B29C 64/268 (2017.01)**

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)

B29C 35/00 –35/08, B33Y 10/00, 30/00, 40/00, G02B 5/00 –5/32, 26/00 –26/12, 27/00 –27/64, G03F 7/00 –7/42.

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)

PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, DWPI, EAPATIS, PATENTSCOPE, Information Retrieval System of FIPS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2017/0361530 A1 (XEROX CORPORATION) 21.12.2017, [0001], [0003], [0004], [0032], [0048], [0049], [0051] –[0055], fig.4 –6	1-2, 5-8, 18, 20
Y		3-4, 9-17, 19
Y	US 2017/0072635 A1 (GLOBAL FILTRATION SYSTEMS DBA GULF FILTRATION SYSTEMS INC) 16.03.2017, [0053], [0057], [0086], fig.1	9-11, 14-17
Y	US 2013/0201081 A1 (BATTELLE MEMORIAL INSTITUTE) 08.08.2013, [0063]-[0073], fig.8	3-4, 12-13, 19
A	WO 2014/130610 A2 (GLOBAL FILTRATION SYSTEMS DBA GULF FILTRATION SYSTEMS INC) 28.08.2014	1-20

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See patent family annex.

* Special categories of cited documents:		"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document but published on or after the international filing date	"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
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
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