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(54) **Title:** TRANSVERSAL LIGHT PIPE

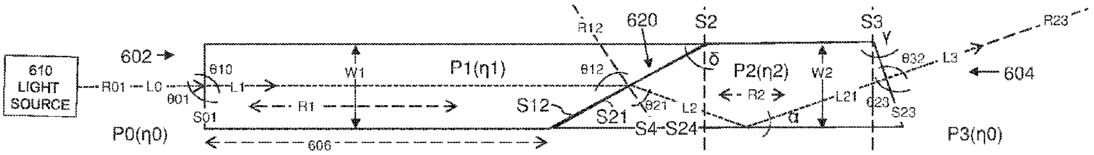

FIG. 3

(57) **Abstract:** A light pipe includes at least two optical structures having different refractive indices. An interface between the two optical structures is oblique to a longitudinal axis of the light pipe such that an output ray from an output surface at a distal end of the light pipe is non-parallel to an input ray that is parallel to the longitudinal axis at an input surface at a proximal end of the light pipe. Light refracts inside the light pipe between the (at least) two optical structures altering the direction of an optical path of the light through the light pipe, thereby allowing higher degrees of freedom for the selection of the angle of deviation (folding angle) of the light pipe. By optimizing various parameters of the light pipe, a desired output optical axis angle (i.e., folding angle) can be achieved that suits the desired optical engine envelope.

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Transversal Light pipe

FIELD OF THE INVENTION

The present invention generally relates to optical light pipes, and in particular, it concerns light pipes that can be used to illuminate electronic display sources (such as liquid crystal on silicon (LCOS) microdisplays used to inject an image into an optical waveguide of a near eye display), having an optical axis (light path) that can be folded at any desired folding angle relative to associated system components.

BACKGROUND OF THE INVENTION

In augmented reality systems, fitting the optical system shape and form factor in an aesthetic wearable frame is a challenge, in particular when mixing different light (e.g., LED) source colors is required. One method of mixing different light source channels together is the use of a light pipe for producing illumination. For aesthetic reasons, it is desirable to have the light pipe aligned with the frame of the glasses. However, light pipes are relatively long elements which often protrude the desired optical engine envelope. Therefore, folding the light pipe in any desired direction is critical in order to achieve an aesthetic shape.

In addition to being relatively long elements, light pipes are typically also relatively straight. In order to somewhat maintain the light pipe in the desired optical engine envelope, curved light pipe designs have been proposed which implement the light pipe as a banded optical fiber. However, banded optical fiber implementations result in low efficiency due to the fact that the rays propagating within the curved banded optical fiber cannot propagate by total internal reflection along the propagation axis. Alternative folding solutions have been proposed in which the light pipe is folded using a right-angled prism (i.e., 90-degree prism) with a reflective coating (i.e., mirror coating). While such solutions yield higher efficiency, these soloutions are significantly limited to specific folding angles.

SUMMARY

According to the teachings of the present embodiment there is provided an apparatus including: a light pipe including at least: (i) a first optical structure having a first refractive index, an input surface at a proximal end of the lightpipe, and a second surface, and (ii) a second optical structure having a second refractive index not equal to the first refractive index, a third surface, and an output surface at a distal end of the lightpipe, the light pipe having a longitudinal axis parallel to a long dimension of the first optical structure in a direction between the input surface, and the second surface, and an interface between the second surface and the third surface being oblique to the longitudinal axis of the light pipe such that an input light ray to the input surface injected parallel to the longitudinal axis is output from the output surface as an output light ray non-parallel to the input light ray.

In an optional embodiment, an angle between the input light ray and the output light ray is an optical angle of deviation of the light pipe, the optical angle of deviation being other than zero degrees. In another optional embodiment, an angle between the longitudinal axis and an output surface normal is a mechanical angle of deviation of the light pipe, the mechanical angle of deviation being other than zero degrees, the output surface normal being normal to the output surface of the second optical structure.

In another optional embodiment, at least the first and second optical structures define an optical path of light through the light pipe, the optical path defined at least in part by the light: coupling-in via the input surface, traversing the first optical structure, refracting from the first to the second optical structures via the interface from the second to the third surfaces, traversing the second optical structure, and coupling out of the second optical structure via the output surface. In another optional embodiment, at least one outer sidewall of the first and second optical structures is coated with a reflective coating, the reflective coating constraining the optical path within the light pipe.

In another optional embodiment, an anti-reflective coating is added to at least one surface of the at least first and second optical structures. In another optional embodiment, the second surface adjoins the third surface. In another optional embodiment, the second surface is separated from the third surface by a gap. In another optional embodiment, the gap filled with a material selected from the group consisting of: air, optical cement, and optical gel. In another optional embodiment, the third surface is configured at a gap angle relative to the second surface.

In another optional embodiment, the first optical structure has a first width and the second optical structure has a fifth width, the fifth width, greater than the first width. In another optional embodiment, a third width of the first optical structure and/or a fourth width of the second optical structure varies along the longitudinal axis of the light pipe. In another optional embodiment, the output surface is at an eighth angle and/or the input surface is at an eleventh angle relative to the longitudinal axis of the light pipe.

In another optional embodiment, further including a light source providing input light to the input surface of the light pipe. In another optional embodiment, further including projecting optics, the light pipe configured to provide the output ray as an input to the projecting optics.

In another optional embodiment, the long dimension of the light pipe is at least an order of magnitude larger than the light pipe width.

According to the teachings of the present embodiment there is provided an apparatus including: a light pipe including at least: a first optical structure having a first refractive index, an input surface at a proximal end of the lightpipe, and a second surface, and a second optical structure having the first refractive index, a third surface, and an output surface at a distal end of the lightpipe, the light pipe having a longitudinal axis parallel to a long dimension of the first optical structure in a direction between the input surface, and the second surface, and an interface between the second surface and the third surface being oblique to the longitudinal axis of the light pipe such that an input light ray to the input surface injected parallel to the longitudinal axis is output from the output surface as an output light ray non-parallel to the input light ray, wherein the second surface is separated from the third surface by a gap.

BRIEF DESCRIPTION OF FIGURES

Some embodiments of the present invention are herein described, by way of example only, with reference to the accompanying drawings. With specific reference to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of embodiments of the invention. In this regard, the description taken with the drawings makes apparent to those skilled in the art how embodiments of the invention may be practiced.

Attention is now directed to the drawings, where like reference numerals or characters indicate corresponding or like components. In the drawings:

FIG. 1, a sketch of an exemplary typical use.

FIG. 2A, a representation of the refraction of the optical path.

FIG. 2B, a variation of the embodiment illustrated in FIG. 2A.

FIG. 3, a sketch of a light pipe corresponding to FIG. 2B,

FIG. 4, a sketch of a light pipe, similar to the light pipe of FIG. 3.

FIG. 5, a sketch of a light pipe similar to the light pipe of FIG. 4.

FIG. 6, a variation of the embodiment illustrated in FIG. 2B.

FIG. 7, a sketch of the light pipe according to the embodiment of FIG. 6.

FIG. 8, a representation of a variation of the embodiment illustrated in FIG. 9.

FIG. 9, a sketch of a light pipe in which the outer sidewalls are tapered.

FIG. 10, a sketch of a light pipe with structures separated by an air gap.

FIG. 11, a light pipe with the distance between the outer sidewalls constant.

FIG. 12, a light pipe with the distance between the outer sidewalls increasing.

FIG. 13A, a sketch of a light pipe constructed from a single base optical structure.

FIG. 13B, a sketch of the light pie of FIG. 13A, with the light in at a different angle.

FIG. 13C, a sketch of a light pipe including a variation of FIG. 13A and FIG. 13B.

FIG. 13D, a sketch of the light pipe of FIG. 13C showing coupling-in loss.

FIG. 13E, a sketch of the light pipe of FIG. 13C and FIG. 13D with TIR

FIG. 13F, a sketch of a light pipe that is a variation of FIG. 13C.

FIG. 13G, a sketch of a variation of in FIG. 13C.

FIG. 13H, a sketch of a variation of FIG. 13G.

FIG. 13I, a sketch of a variation of FIG. 13A and FIG. 13G.

FIG. 14A, a sketch of an alternative implementation of a light pipe.

FIG. 14B, a sketch of a variation of FIG. 14A.

FIG. 14C is a sketch of a variation of FIG. 13C, FIG. 13E, and FIG. 13G, in which the diffuser is placed at the output of the additional optical structure.

FIG. 15A, a sketch of a side view and a top view of the light pipe of FIG. 13C to FIG. 13I.

FIG. 16A, a sketch of a conventional folded light pipe using a reflective coating.

FIG. 16B, a sketch of an improved light pipe.

FIG. 16C, a sketch of FIG. 16B, in three-dimensions (3D) and with alternative tilt and rotation of the input and output surfaces.

DETAILED DESCRIPTION - FIRST EMBODIMENT – FIGS. 1 to 16C

Embodiments of the present invention are directed to light pipes which provide an optical path that can be folded at any desired folding angle.

Unless otherwise defined, all technical and/or scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the invention pertains. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of embodiments of the invention, exemplary methods and/or materials are described below. In case of conflict, the patent specification, including definitions, will control. In practice or testing of embodiments of the invention, exemplary methods and/or materials are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and are not intended to be necessarily limiting.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings and/or the Examples. The invention is capable of other embodiments or of being practiced or carried out in various ways.

Note that for simplicity in the figures, only one light ray is generally depicted. The light ray can also be referred to as “light” or a “beam”. One skilled in the art will realize that the depicted light (ray) is a sample beam of the actual light, which typically is formed by multiple beams, at slightly differing angles. Except where specifically referred to as an extremity (edge) of the light, the rays illustrated are typically a centroid of the light. In a case wherein the light corresponds to an image and the central ray is a center ray from a center of the image or a central pixel of the image. In a case wherein the light is coming from a light source, the central ray is typically the center (and maximum intensity) of a cone of illumination propagating from the light source.

The illumination light pipe according to embodiments of the present invention is formed from a combination of at least two (i.e., two or more) optical structures (e.g., prisms), namely a first optical structure and a second optical structure. The first optical structure is formed from a material having a first index of refraction, and the second optical structure is formed from a material having a second index of refraction different from the first index of refraction. Light refracts inside the light pipe between the (at least) two optical structures in accordance with Snell’s law. Accordingly, the optical path of the light pipe is bent before the light exits the optical structures, thereby allowing higher degrees of freedom for the selection of the folding angle (defined below). By optimizing various parameters of the light pipe, a desired output optical axis angle (i.e., folding angle) can be achieved that suits the desired optical engine envelope. The optimizable parameters include, for example, the refractive indices of the optical structures, the angle(s) of the internal optical junction(s), the orientation angles of the external surfaces of the optical structures, and the orientation angles of the entrance and exit surfaces of the optical structures.

The following paragraphs describe different embodiments of the light pipe of the present invention. The following embodiments are exemplary only, and the invention should not be limited to the particular embodiments described herein. Other embodiments of the light pipe are contemplated as well.

Refer now to FIG. 1, a sketch of an exemplary typical use of an embodiment of a light pipe **600** of the current invention. For aesthetic reasons, the lightpipe **600** is preferably aligned (parallel) to a frame (**FRAME**) of glasses, shown in the current figure as a longitudinal axis **R1** of the lightpipe **600** parallel to the frame. A light source beam from a light source **610** provides input light to the light pipe **600**, in this case to an input surface (not shown) along an input surface normal **R01**. The light pipe diverts the optical axis, changing the direction of the optical path through the lightpipe **600** such that an output light ray along an output surface normal **R23** is non-parallel to the input ray along the input surface normal **R01**. In this case, the illumination output of the light pipe **600** is directed to projecting optics **612**, that feeds an image to an image expansion module for viewing by a user's eyes. In the context of this document, the light pipe diverting the optical axis is sometimes referred to as "folding" the optical axis.

With reference to FIG. 2A, a representation of the refraction of the optical path of a light pipe according to an embodiment of the present invention in which two optical structures are used. For clarity, the external sides of the light pipe are not shown. A light pipe **600A** has an input end **602** deployed in a first base medium **P0** (e.g., air) having a base refractive index η_0. In the figures, general references are to a light pipe as element **600**, and specific embodiments as elements **600x**, where "x" is a letter. It will be obvious to one skilled in the art that some descriptions of specific embodiments **600x** are applicable to the general light pipe **600** and other specific embodiments **600x**. A first optical structure **P1** (for example, a component or element, such as a prism) has a first refractive index of η_1 and a second optical structure **P2** (component, element) has a second refractive index of η_2. The medium at an output end **604** of the light pipe **600** is generally the same medium as at the input end **602** of the light pipe **600**. This implementation is not limiting, and the output end **604** can be in a second medium **P3**, other than the first base medium **P0**. For clarity in this description, the medium at the output end **604** of the light pipe **100** is generally shown as the second medium **P3**. In a case where the second medium **P3** has refractive index different from the first medium's **P0** base refractive index η_0, the second medium **P3** index of refraction is referred to as a third refractive index η_3. In the current example, the second medium **P3** has the base refractive index η_0, the same refractive index and the same medium as the base medium **P0**. In the current example, the refractive indices of the first **P1** and second **P2** optical structures are different. This implementation is not limiting, and as described below, in alternative configurations, the refractive indices of the optical structures can be substantially equal.

A light source **610** provides light to the light pipe **600A**. Light sources are known in the art, for example, a group of multiple LEDs where each LED radiates one color of light, the combination of colors being the light provided by the light source. A typical exemplary source provides a combination of colors from three LEDs, one LED producing red light, one LED producing green light, and one LED producing blue light. The light source **610** provides light in that is represented as input light ray **L0** (also referred to as a "beam" or "input beam"). The combination of colors, also known as light source channels, are mixed by the light pipe to produce an illumination output, typically substantially white light.

As the base medium **P0** and the first optical structure **P1** have different indices of refraction, the input ray **L0** will be refracted at an external input surface **S01** to ray **L1** (first optical structure **P1** ray **L1**) internal to the first optical structure **P1**. The external input surface **S01** of the first optical structure **P1** of the light pipe **600A** has a normal shown as dashed line input surface normal **R01** in the direction of the base medium **P0**. Correspondingly, the input surface normal **R01** is also normal to the first optical structure **P1** internal side of the input surface **S01**, the internal side opposite the external side of the input surface **S01**. A first angle, external input angle θ_{01} is defined between the input ray **L0** and the input surface normal **R01**. Similarly, a second angle is an internal input angle $\boldsymbol{\theta_{10}}$ is defined between the ray **L1** and the input surface normal **R01**.

The ray **L1** propagates from the external input surface **S01** via the first optical structure **P1** to a second surface **S12**. In this case, the second surface **S12** is an output surface of the first optical structure **P1** in a direction of the second optical structure **P2**. The second surface **S12** adjoins a third surface **S21** that is an input surface to the second optical structure **P2**. Typically, the second surface **S12** and the third surface **S21** are configured adjacent and in contact with each other, effectively implementing a single interface **620** between the first optical structure **P1** and the second optical structure **P2**. For convenience in the current description, the interface **620** of the second surface **S12** and the third surface **S21** is generally referred to simply as the "second surface **S12**". Note, in the current figure, the second surface **S12** and the third surface **S21** are each represented by lines that are slightly separated in the drawing for clarity (instead of using a single line that is the practical implementation of the current example). This implementation is not limiting, and described below are implementations where surfaces of optical structures are not adjacent.

As the first optical structure **P1** and the second optical structure **P2** have different indices of refraction, the ray **L1** will be refracted at the second surface **S12** to ray **L2** (second optical structure **P2** ray **L2**) internal to the second optical structure **P2**. The second surface **S12** of the first optical structure **P1** has a normal shown as dashed line second surface normal **R12** in the direction of the first optical structure **P1**. Correspondingly, the second surface normal **R12** is also normal to the second optical structure **P2** internal side of the third surface **S21**. A third angle, second surface output angle θ_{12} is defined between the ray **L1** and the second surface normal **R12**. Similarly, a fourth angle is a third surface input angle θ_{21} is defined between the ray **L2** and the second surface normal **R12**.

The ray **L2** propagates from the third surface **S21** via the second optical structure **P2** to an output surface **S23**. In this case, the output surface **S23** is a fourth surface of the second optical structure **P2** in a direction of the second medium **P3**. As the second optical structure **P2** and the second medium **P3** have different indices of refraction, the ray **L2** will be refracted at the output surface **S23** to ray **L3** (second medium **P3** ray **L3**) internal to the second medium **P3**. Ray **L3** is the light out of the light pipe **600**. The output surface **S23** of the second optical structure **P2** has an output normal shown as dashed line output surface normal **R23** (also referred to in the context of this document as a fourth surface normal) in the direction of the second optical structure **P2**. Correspondingly, the output surface normal **R23** is also normal to the second medium **P3** external side of the output surface **S23**. A fifth angle, fourth surface output angle θ_{23} is defined between the ray **L2** and the output surface normal **R23**. Similarly, a sixth angle is a fourth surface output angle θ_{32} is defined between the ray **L3** and the output surface normal **R23**.

Two construction lines are used in the current figure. A second reference line **S2** and a third reference line **S3** both parallel to the input surface **S01**. The second reference line **S2** intersects the second surface **S12**. A seventh angle (δ, “delta”) is defined between the second reference line **S2** and the second surface **S12** (in this case, also the third surface **S21**). The seventh angle (δ) is used to help define the orientation of surfaces between the first optical structure **P1** and the second optical structure **P2**. Similarly, the third reference line **S3** intersects the output surface **S23**. An eighth angle (γ, “gamma”) is defined between the third reference line **S3** and the output surface **S23**. The eighth angle (γ) is used to help define the orientation of surfaces between the second optical structure **P2** and the second medium **P3**.

An input optical axis is defined as coinciding with the input ray **L0**, as described above the central ray of the input light. The light rays, in this case the ray **L1** and the ray **L2** form an optical axis, or optical path, of propagation through the light pipe **600** (through the first **P1** and the second

P2 optical structures). An output optical axis is defined as coinciding with the output ray **L3**, the central ray of the output light. References to the "optical path", for example propagation through the light pipe **600**, and bending of the optical path, may also be referred to as the "optical axis", for example the optical axis of the light propagating through the light pipe **600** and bending of the optical axis. One skilled in the art will understand that an input ray that is off axis (non-normal to the input surface **S01**, non-parallel to the input surface normal **R01**) will normally be reflected several times on the light pipe **600** walls. An exemplary off-axis optical path **L9** is shown in the current figure.

In the current embodiment, the optical path is (optical axes are) refracted at least three times. First, the input optical axis (ray **L0**) of the optical path is refracted from the first medium **P0** having refractive index η_0 to the first optical structure **P1** having a refractive index of η_1. Then the optical path is refracted from the first optical structure **P1** having a refractive index of η_1 to the second optical structure **P2** having a refractive index of η_2. Then the optical path is refracted from the second optical structure **P2** having a refractive index of η_2 to the second medium **P3** having refractive index η_0.

The angles of incidence and angles of refraction are as follows:

$$\eta_0 * \sin(\theta_{01}) = \eta_1 * \sin(\theta_{10})$$

$$\eta_1 * \sin(\theta_{12}) = \eta_2 * \sin(\theta_{21})$$

$$\eta_2 * \sin(\theta_{23}) = \eta_0 * \sin(\theta_{32})$$

$$\theta_{12} = \theta_{10} - \delta$$

$$\theta_{23} = \theta_{21} - (\delta - \gamma)$$

In addition, the two refractive indices η_1 to η_2 are both larger than the refractive index of the base medium η_0. Respectively the first refractive index η_1 and the second refractive index η_2 are larger than the base refractive index η_0. As such, either $\eta_1 \geq \eta_2 \geq \eta_0$, or $\eta_2 \geq \eta_1 \geq \eta_0$.

Given the above discussion and using the current exemplary embodiment, we can now discuss a definition of a folding angle of the light pipe **600**. In the context of this document, the term "angle of deviation" (or "folding angle") can be defined with respect to the light, that is, from the "light's point of view" (an "optical angle of deviation" or "optical folding angle"), or relative to the direction of the input optical axis (light input ray **L0**) and the output optical axis (light output ray **L3**) (a "mechanical angle of deviation" or "mechanical folding angle"). Where the terms "angle of deviation" or "folding angle" are used without specifying optical or mechanical, one skilled in the art will understand that reference includes both optical and mechanical. In this case, the optical folding angle of the light pipe **600** is an angle defined between the input light ray **L0** and the output light ray **L3**. As discussed above, by choosing, configuring, and optimizing various parameters of the light pipe **600**, a desired folding angle can be achieved that suits the desired optical engine envelope. Examples of the parameters include, the refractive indices (η_0, η_1, η_2, η_3) of the optical structures (**P0**, **P1**, **P2**, **P3**), the angle(s) of the internal optical junction(s) (δ), the orientation angles (α, β) of the external surfaces of the optical structures, and the orientation angles of the entrance and exit surfaces of the optical structures (ψ, γ). Note, element notation in the previous sentence not yet described, is described below.

Based on the current description, given a desired direction of the output ray **L3**, the folding angle can be determined, and a light pipe **600** designed for any folding angle, including zero degrees (0°) and 90°, and in particular other than zero degrees (0°) and 90°, that is, with an output optical axis other than straight and normal to the input optical axis.

FIG. 2B shows a variation of the embodiment illustrated in FIG. 2A. Optionally, the outer sidewalls (also referred to in the context of this document as "outer walls") can be coated with a reflective coating layer. In the current embodiment, a first outer sidewall **S24** of the light pipe **600B** can be coated with a reflective coating layer such that the optical path (in this case ray **L2**) is additionally reflected at a specific angle (a ninth angle, α, "alpha") inside the light pipe **600B** by the first outer sidewall **S24** to a ray **L21**. Alternatively, or in addition, the light pipe **600** can be configured so the outer sidewalls (in this case the first outer sidewall **S24**) use total internal reflection (TIR) to reflect one or more portions of the optical path. A fourth reference line **S4** is a construction line perpendicular to the input surface **S01**. The fourth reference line **S4** intersects the first outer sidewall **S24**. The ninth angle (α) is defined between the fourth reference line **S4** and the first outer sidewall **S24**. The ninth angle (α) is used to help define the orientation of the first outer sidewall **S24** with respect to the other surfaces of the light pipe **600**. In the current embodiment, the angle of incidence θ_{23} of the ray **L21** before returning the base medium is given by the equation $\theta_{23} = \theta_{21} - (\delta - \gamma) - 2\alpha$.

FIG. 3 is a sketch of a light pipe **600C** corresponding to FIG. 2B, whereby the optical path (**L0**, **L1**, **L2**, **L21**, **L3**) is refracted due at least in part by the change in refractive indices of the two optical structures (P1, P2), and is reflected by one of the outer sidewalls (the first outer sidewall

S24) of the light pipe **600**. Note in the current figure that the input light ray **L0** is normal to the external input surface **S01** the input light ray **L0** is parallel to the input surface normal **R01**, the external input angle θ_{01} is 90°, and the internal input angle θ_{10} is 90°. Note also that the output light ray **L3** is normal to the output surface **S23**, the output light ray **L3** is parallel to the output surface normal **R23**, the fourth surface output angle θ_{23} is 90°, and the external output angle θ_{32} is 90°.

In the above description, the folding angle was defined with respect to the light, that is from the "light's point of view" or relative to the direction of the light input ray **L0** and the light output ray **L3**. Alternatively, the folding angle can be described with respect to the mechanical configuration of the elements of the light pipe **600**. A longitudinal axis **R1** is defined parallel to a long dimension **606** of the first optical structure **P1**. Note, the longitudinal axis **R1** is not restricted to being normal to the input surface **S01** nor parallel to the input light ray **L0**. In the current example, the longitudinal axis **R1** is normal to the input surface **S01** and is parallel to the input light ray **L0**. In the examples of FIG. 2A and FIG. 2B the longitudinal axis **R1** is may or may not be normal to the input surface **S01**, and is not parallel to the input light ray **L0**. The longitudinal axis **R1** serves as an input reference for the folding angle. The output surface normal **R23** serves as an output reference for the folding angle. The mechanical folding angle is then defined by an angle between the longitudinal axis **R1** and the output surface normal **R23**.

In the figures, the input surface **S01** is generally drawn perpendicular to the longitudinal axis **R1** of the first optical structure **P1**, however, this implementation is not limiting, and as described elsewhere the input surface **S01** can be non-perpendicular (slanted at an angle other than 90°, or oblique) to the longitudinal axis **R1** of the first optical structure **P1**.

The second optical structure **P2** is typically in line with the first optical structure **P1**, so a second longitudinal axis **R2** of the second optical structure **P2** is typically the same, parallel, or substantially in the same direction as the first longitudinal axis **R1** of the first optical structure **P1**. This implementation is not limiting, and one skilled in the art will understand that the second longitudinal axis **R2** of the second optical structure **P2** can be in a direction other than the direction of the first longitudinal axis **R1**. In the current description, to assist with clearly defining an overall effect of the light pipe **600**, the output of the second optical structure **P2** is defined relative to the first optical structure **P1**, (and the first longitudinal axis **R1**).Note that in the figures, for simplicity the optical structure surfaces (for example, the input surface **S01**, the first outer sidewall **S24**, and the output surface **S23**) are generally drawn as flat surfaces (straight lines), however, this implementation is not limiting, and surfaces of the optical structures can be other shapes, such as curved. For example, the input surface **S01**, the second surface **S12**, and/or the output surface **S23** can be curved, thus implementing a lens at the respective input and output of the light pipe.

While the output surface **S23** can be a variety of shapes, for ease of manufacturing and mechanical attachment to follow-on devices, a straight surface that is also perpendicular to sides of the light pipe **600** is often preferred.

In the figures, a first width **W1** of the first optical structure **P1** is generally drawn substantially equal to a second width **W2** of the second optical structure **P2**. Widths of the optical structures are not necessarily equal, as some of the below described examples detail. Widths of the optical structures are generally along a short axis of the light pipe **600** as compared to a long axis (such as the longitudinal axis **R1**) of the light pipe **600**, in other words, typically perpendicular to the longitudinal axis **R1**.

FIG. 4 is a sketch of a light pipe **600D**, similar to the light pipe **600C** of FIG. 3. In the current figure, the optical path, ray **L1**, undergoes an additional reflection **640** by Fresnel reflection internal to the first optical structure **P1** at the second surface **S12**, reflecting a ray **L12** toward a fourth outer sidewall **S15** of the light pipe **600D**. A second additional reflection **642** (by total internal reflection) at the fourth outer sidewall **S15** reflects a ray **L13** toward the second surface **S12**. The ray **L13** refracts from the first optical component **P1** to the second optical component **P2**, continuing along the light path as described above.

FIG. 5 is a sketch of a light pipe **600E** according to another embodiment, similar to the light pipe **600D** of FIG. 4. In the current embodiment, the optical structures are implemented as two prisms constructed from the same material and separated by a gap **650**, in this case an air gap. In this case, the interface **620** includes the area of the second surface **S12**, the third surface **S21**, and the gap **650**. A first prism is the first optical structure **P1** having the first refractive index of η_1 and a second prism **P11** is an other optical structure having the first refractive index of η_1. As described above, this exemplary implementation is not limiting, and two or more optical structures can be used. Two or more of the optical structures can have different refractive indices, or two or more of the optical structures can have the same refractive indices. Outer sidewalls are designated for the second optical structure **P2** as the first outer sidewall **S24**, a second outer sidewall **S25**, and designated for the first optical structure **P1** as a third outer sidewall **S14** and a fourth outer sidewall **S15**. The angle and spacing of the (air) gap **650** with respect to the outer sidewalls (**S14**, **S15**, **S24**,

S25) of the prisms (**P1**, **P11**) and an angle of the optical structure surfaces (the second surface **S12** and the third surface **S21**, for example, can be parallel or non-parallel to each other) is determined such that the whole range of useful rays propagating inside the light pipe (between rays **652**) are reflected at the air gap by total internal reflection, then reflection off of the fourth outer sidewall **S15** (by total internal reflection), are again incident at the air gap at angles less than the critical angle and are thereby transmitted from the first prism **P1** via the air gap **650** to the second prism **P11**. As a result, the beam (between rays **652**) is narrowed (range between beams **654**) and diverted. In the event that there are reflections off of the first prism **P1** upper fourth outer sidewall **S15**, following reflection at the air gap **650**, are incident below the critical angle to prevent transmission at the air gap **650**, a mirror (e.g., a reflective coating or a reflective surface) may be applied to the region of the upper fourth outer sidewall **S15** at which reflection occurs.

FIG. 6 shows a variation of the embodiment illustrated in FIG. 2B with additional components illustrated in FIG. 7 where there are two internal reflections of the principal ray (light path **L0**, **L1**, **L2**, **L21**, **L22**, **L3**). In the current embodiment, in the second optical structure **P2** the first outer sidewall **S24** of the light pipe **600F** can be coated with a reflective coating layer such that the optical path (in this case ray **L2**) is additionally reflected at a specific angle (a ninth angle, α, "alpha") inside the light pipe **600F** by the first outer sidewall **S24** to a ray **L21**. Similarly, the second outer sidewall **S25** of the light pipe **600F** can be coated with a reflective coating layer such that the optical path (in this case ray **L21**) is additionally reflected at a specific angle (a tenth angle, β) inside the light pipe **600F** by the second outer sidewall **S25** to a ray **L22**. Alternatively, or in addition, the light pipe **600** can be configured so the outer sidewalls (in this case the first outer sidewall **S24** and the second outer sidewall **S25**) use total internal reflection (TIR) to reflect one or more portions of the optical path

A fifth reference line **S5** is a construction line perpendicular to the input surface **S01**. The fifth reference line **S5** intersects the second outer sidewall **S25**. The tenth angle (β) is defined between the fifth reference line **S5** and the second outer sidewall **S25**. The tenth angle (β) is used to help define the orientation of the second outer sidewall **S25** with respect to the other surfaces of the light pipe **600**. In this embodiment, the angle of incidence θ_{23} of the optical axis before returning the second medium **P3** is given by the equation $\theta_{23} = \theta_{21} - (\delta - \gamma) - 2 * \alpha - 2 * \beta$.

FIG. 7 is a sketch of the light pipe **600F** according to the embodiment of FIG. 6. For clarity, not all of the elements of FIG. 6 are shown. In the current figure, the sidewalls (**S24**, **S25**) of the second optical structure **P2** are parallel to each other and perpendicular to the input surface **S01**.

Thus, the fourth reference line **S4** is parallel, coinciding with the first outer sidewall **S24** and the ninth angle (α) is zero (0°). Similarly, the fifth reference line **S5** is parallel, coinciding with the second outer sidewall **S25** and the tenth angle (β) is zero (0°).

FIG. 8 shows a representation of a variation of the embodiment illustrated in FIG. 9, further including the input surface **S01** is angled. In combination with any of the above-described embodiments, the light pipe **600** can be angled such that the entrance surface, the external input surface **S01** (i.e., the interface between the base medium **P0** and the first optical structure **P1**) is tilted at a specific angle (an eleventh angle, ψ, “psi”). Note that representation shown in FIG. 8 is the representation shown in FIG. 6 with an additional tilt angle ψ. A tilt angle can be applied to other representations as well, such as FIG. 2B. Similar to the above descriptions, A sixth reference line **S6** is a construction line, now used as a reference in place of the input surface **S01**, as the input surface **S01** is now tilted. The sixth reference line **S6** intersects the input surface **S01**. The eleventh angle (ψ) is defined between the sixth reference line **S6** and the input surface **S01**. The eleventh angle (ψ) is used to help define the orientation of the input surface **S01** with respect to the other surfaces of the light pipe **600G**.

FIG. 9 is a sketch of a light pipe **600G** according to another embodiment of the present invention in which the outer sidewalls of the light pipe (i.e., the outer sidewalls of the two optical structures) are tapered, resulting in a light pipe with tapered sidewalls. The first optical structure **P1** has the first width **W1** at the input end **602** which in the current figure is also the width of the input surface **S01**. The first optical structure **P1** increases in width along the longitudinal axis **R1** in the direction of the optical path (ray **L1**) to a third width **W11** near the second surface **S12**. The second optical structure **P2** has a fourth width **W22** near the third surface **S21**. The second optical structure **P2** decreases in width along the longitudinal axis **R1** in the direction of the optical path (**L2, L21, L22**), from the second surface **S12** toward the output surface **S23**, to the second width **W2** near the output surface **S23**. Alternatively, (not shown in the current figure) the first optical structure **P1** can decrease or remain constant in width and the second optical structure **P2** can increase or remain constant in width along the longitudinal axis **R1**.

In the current figure the ninth angle (α) and the fourth reference line **S4** for the first outer sidewall **S24** are shown, as well as the tenth angle (β) and the fifth reference line **S5** for the second outer sidewall **S25**. The corresponding reference lines and angles are not shown for the third outer sidewall **S14** and the fourth outer sidewall **S15**. Based on this description, one skilled in the art will be able to handle these elements appropriately.

FIG. 10 is a sketch of a light pipe **600I** in which different structures (parts) of the light pipe, with equal junction surface angle, are separated by an air gap **660**. The optical structures, in the current exemplary figure are two structures (**P1**, **P2**) that can have the same or different refractive indices. The current figure is similar to FIG. 5. In the current exemplary figure, the second surface **S12** and the third surface **S21** are at a gap angle **1000** to each other, as compared to the exemplary embodiment of FIG. 5 where the second surface **S12** and the third surface **S21** are parallel to each other. In this case, the interface **620** includes the area of the second surface **S12**, the third surface **S21**, and the gap **660**. While the second surface **S12** is perpendicular to the longitudinal axis **R1** (and parallel to the input surface **S01**), the third surface **S21** is oblique to the longitudinal axis **R1**, and thus the interface **620** is considered oblique to the longitudinal axis **R1** of the light pipe **600**.

FIG. 11 and FIG. 12 are sketches of light pipes (**600J**, **600K**) in which different optical structures (**P1**, **P2**) are separated by a gap **670** optionally filled with an optical medium **672** having a corresponding gap refractive index η_4. In this case, the interface **620** includes the area of the second surface **S12**, the third surface **S21**, the gap **670**, and the optical medium **672**. Optical mediums include, for example, as optical cement and optical gel. At least two different refractive indices should be used for the three structures [the first optical structure P1(η_1), the second optical structure P2(η_2), the gap **670** (η_4)] so the optical path is refracted along the longitudinal axis **R1**. While the current figure is drawn with the gap **670** being between parallel surfaces, in this case the second surface **S12** and the third surface **S21**, this implementation is not limiting, and the gap **670** can include gap angle **1000** as described in reference to FIG. 10. In implementations in which the separation is by an optical medium, in order to improve efficiency, the distance (width) between the outer sidewalls of the light pipe can be increased (i.e., widen the light pipe) at the section of the light pipe after the interface **620** of two different refractive indices. In this case, widening the second optical structure **P2**. Optionally, one or more anti-reflective coatings can be added between the different optical structures, for example, to improve efficiency of light transmission from the first **P1** to second **P2** optical components.

FIG. 11 shows a light pipe **600J** in which the distance between the outer sidewalls remains constant – in this case resulting in light loss, i.e., reduced efficiency. In the current figure, the first width **W1** of the first optical structure **P1** is substantially equal to the second width **W2** of the second optical structure **P2**. A portion of output rays **L33** are in a band **W33** that will not exit the light pipe **600J** together with the rest of the beam (the output light rays **L3**), but will rather have an additional reflection off of the upper surface (the first outer sidewall **S24**), and will be lost to the system (not output within a useable range of output angles from the output surface **S23**).

FIG. 12 shows a light pipe **600K** in which the distance between the outer sidewalls (the first outer sidewall **S24** and the second outer sidewall **S25**), in the section after the interface **620** (after the gap **670**, the second optical structure **P2**), is increased from the second width **W2** to a fifth width **W23** – thereby preserving efficiency as can be seen by all of the output rays **L31** being output from the output surface **S23**. In this case, the fifth width **W23** is greater than the second width **W2**. The result is the light pipe **600K** having a second section (corresponding to the second optical structure **P2**, i.e., prism) that is wider than a first section (corresponding to the first optical structure **P1**, i.e., prism).

FIG. 13A is a sketch of a light pipe **1300A** constructed from a single base optical structure **1310** formed as a slab-type structure having slanted entrance **1302** and exit **1304** surfaces. The optical structure **1310** can be formed by taking a rectangular slab and making corresponding diagonal cuts at the ends of the slab. The resultant light pipe **1300A** has a trapezoidal shape in the cross-section of the plane of the paper. When implemented as an isosceles trapezoid, the angle of incidence of input light **L0** entering the light pipe **1300A** through the entrance surface **1302**, and the angle of the light coupled out **L4** of the light pipe **1300A** through the exit surface **1304**, are equal.

FIG. 13B is a sketch of the light pie **1300A** of FIG. 13A, with the light in **L0** at a different angle relative to the entrance surface **1302**. Although the light pipe **1300A** shown in FIG. 13A has the advantage of being formed from a single structure (base **1310**), the light pipe **1300A** may suffer from coupling-out light loss, i.e., reduced efficiency as shown by output light **L5** coupling out from an outer wall of the light pipe **1300A**, not coupling out from the output surface **1304**.

FIG. 13C is a sketch of a light pipe **1300B** including a variation of the embodiment illustrated in FIG. 13A and FIG. 13B. The current embodiment, lightpipe **1300B**, avoids coupling-out light **L5** loss, thereby preserving efficiency. In this embodiment, an additional optical structure **1312**, in the form of a coupling-out wedge (e.g., prism), is attached to the single base optical structure **1310**. In this case, the previous exit surface **1304** of the single optical structure can be replaced by forming an exit surface **1306** of the single base optical structure **1310** by making a vertical cut at the right end (non-limiting directional reference as drawn on the sheet) of the single base optical structure **1310** resulting in a right trapezoid in the cross-section of the plane of the paper. The two optical structures (**1310**, **1312**) may have different refractive indices, or may have the same refractive indices so as to prevent unwanted reflections/refractions at the junction surface (i.e., interface **620**) between the two optical structures (**1310**, **1312**). The lightpipe **1300B** now has a new output surface **1308** from the additional optical structure **1312**.

FIG. 13D is a sketch of the light pipe **1300B** of FIG. 13C showing coupling-in loss. Although the current light pipe **1300B** avoids coupling-out light loss **L5**, the light pipe **1300B** may be subject to coupling-in light loss **L6** due at least in part to a refractive index of the material from which the single base optical structure **1310** is formed. As seen in the current figure, if the refractive index of the single base optical structure **1310** is not high enough, some of the light rays **L0** entering the single base optical structure **1310** through the entrance surface **1302** may be refracted at a steep angle, such that, when the refracted light rays strike the bottom surface of the single base optical structure **1310**, the refracted light rays may not undergo total internal reflection within the single base optical structure **1310**. Therefore, the material(s) from which the two optical structures (**1310**, **1312**) are formed is/are preferably of high enough refractive index (preferably 1.60 and above) such that light rays entering **L0** the single base optical structure **1310** through the entrance surface **1302** are refracted at a shallow enough angle so as to undergo total internal reflection (TIR) when striking the bottom surface of the single base optical structure **1310**.

FIG. 13E is a sketch of the light pipe **1300B** of FIG. 13C and FIG. 13D where the single base optical structure **1310** is made from a material of high enough index of refraction that the input light **L0** is refracted at the input surface **1302** at a high enough angle to result in TIR when striking the bottom surface of the single base optical structure **1310**.

FIG. 13F is a sketch of a light pipe **1300C** that is a variation of the light pipe **1300B** of FIG. 13C. In the current figure, an input surface **1302A** is “flipped” vertically on the sheet from the input surface **1302**, providing the single base optical structure **1310** with an input surface **1302A** rotated 90° from the input surface **1302** of the previously described lightpipe **1300B**. The functionality of both light pipes (**1300B**, **1300C**) is maintained.

FIG. 13G is a sketch of a variation of the embodiments illustrated in FIG. 13C. The light pipe **1300B** is part of an optical apparatus in which a collimating lens **1320** is deployed at or near the entrance surface **1302** of the single base optical structure **1310** (i.e., trapezoidal structure). The use of a collimating lens reduces the angular range of the light source beam **L7**, reducing coupling-in loss of the input light ray **L0** to the lightpipe **600**.The collimating lens **1320** may be attached to the entrance surface **1302** via optical cement, or may be deployed near the entrance surface **1302** with an air gap maintained between the collimating lens **1320** and the entrance surface **1302**. In embodiments in which an air gap is maintained, the collimating lens **1320** can be held in place via a mechanical arrangement. The light source **610** provides light to the collimating lens **1320** that collimates the provided light and outputs a collimated beam **L01** of light to the entrance surface **1302**. The current configuration results in a collimated output beam **L31**.

FIG. 13H is a sketch of a variation of the embodiment illustrated in FIG. 13G. In the current embodiment, a Fresnel lens **1330** is used instead of the collimating lens **1320**. The use of the Fresnel lens **1330** has an advantage of providing light rays **L01** covering a wider range of angles to the entrance surface of the single base optical structure **1310**, as compared to use of the collimating lens **1320**. Another advantage of using the Fresnel lens **1330** is mechanical, providing a smaller focal length for the same volume compared to the collimating lens **1320**. The Fresnel lens **1330** can be configured in an optical apparatus with the single base optical structure **1310** similar to the above-described deployment of the collimating lens **1320**, for example with optical cement or an air gap.

FIG. 13I is a sketch of a variation of the embodiments illustrated in FIG. 13A and FIG. 13G. In the current embodiment, a pyramid **1340** (made for example of glass or plastic) is used instead of the collimating lens **1320**. The use of the pyramid **1340** has an advantage of using reflection instead of refraction. The pyramid **1340** collects the light source beam **L7**, better than the collimating lens **1320**, in part because the light source **610** (for example, LEDs) can be brought in contact with the pyramid **1340** entrance. Typically, when using a regular lens, such as the collimating lens **1320**, a distance needs to be kept between the light source **610** and the lens surface. For example, the source may need to be at a focal plane of the lens to work properly. As a result, high angle rays are lost from the light source beam **L7**. Using the pyramid **1340**, relatively more high angle rays can be collected from the light source beam **L7**. In an alternative embodiment, instead of using the pyramid **1340**, a reflective lens with a curved (non-straight) side wall can be used. The pyramid **1340** can be configured in an optical apparatus **1300D** with the single base optical structure **1310** similar to the above-described deployment of the collimating lens **1320**, for example with optical cement or an air gap.

In the current figure, the output of the single base optical structure **1310** is the exit surface **1304** as described above with reference to FIG. 13A. In the current embodiment, a diffuser **1350** is configured adjacent to the exit surface **1304**. One exemplary advantage of using a diffuser is for better color mixing. The use of a diffuser at the output of the lightpipes and as a component of the optical apparatus is an optional embodiment.

According to certain embodiments, the optical structures which form the light pipe can be arranged such that the optical axis **R01** at the entrance surface/aperture **S01** (i.e., the interface between the base medium **P0** and the first optical structure **P1**) is orthogonal to the optical axis **R23** at the exit surface/aperture **S23** (i.e., the interface between the second optical structure **P2** and the base medium **P3**).

According to certain embodiments, an anti-reflection coating can be applied to the junction surface (i.e., the interface **620**, where two surfaces are adjacent, or on a surface adjacent to an air gap) between two optical structures that form the light pipe.

According to certain embodiments, a reflective coating can be applied to some or all of the outer surfaces (outer sidewalls) of the light pipe.

According to certain embodiments, an index matched optical cement or optical gel can be deployed between the two optical structures that form the light pipe. The refractive index of the optical cement or optical gel can be matched to one of the juxtaposed materials from which the optical structures are constructed.

According to certain embodiments, an optical cement or optical gel having a deliberately unmatching refractive index can be deployed between the two optical structures that form the light pipe.

One skilled in the art will understand the typical dimensions and requirements for general light pipe operations. For example, the long dimension (**606**) of the light pipe (**600**) is typically referred to as the length of the light pipe **600**, and is significantly longer (for example, an order of magnitude larger) than the short dimension (width) of the light pipe. A cross-section of the light pipe **600** is typically rectangular, however, this is not limiting, and other cross-sections can be used, for example, round. A typical thickness of the light pipe **600** is from 1 to 5 mm. A typical length of the light pipe **600** is from 10 to 60 mm.

The light pipe **600** conveys light (the input light ray **L0**) from the input surface **S01** to the output surface **S23**, preferably with negligible loss of illumination intensity. Embodiments of the current invention change the orientation of the incoming light, the light entering the light pipe **600** with a given aperture and exiting the light pipe **600** with a substantially similar aperture. The optical path of the light is redirected, a deviation of the optical path through the light pipe **600**.

The range of angles of the input light can vary. For example, the light in **L0** can be at an external input angle θ_{01} between 0 ° and +-60° (for simplicity referred to as just +-60°). **L0** can be any of the rays of a cone of light originating at the light source **610** and impinging on the external input surface **S01**. Another non-limiting example, the input light **L0** can be non-symmetric around the input surface normal **R01**, for example between the angles of -30 ° and +40 °. LED sources in current use include possible input of +-90°. Similarly, the light out **L3** can be at an output angle θ_{32} between 0 ° and +-60° (for simplicity referred to as just +-60°). Another non-limiting example, the light out **L3** can be non-symmetric around the output surface normal **R23**, for example between the angles of -20 ° and +30 °. One preferred implementation is an output range of +-40 °. The light pipe **600G** of FIG. 9 can be used to change the range of angles of the light out **L3**. For example, tapering the second optical structure **P2** can be used to reduce the range of output angles and/or to concentrate the propagating light rays into an angle of interest. Similarly, if the range of input angles is broader (greater) than a desired range at the output, the second optical structure **P2** can be tapered to reduce the output range of angles. Similarly, if the range of input angles is narrower (smaller) than a desired range at the output, the second optical structure **P2** can be increased in width (**W22** to **W2**) to increase the output range of angles.

FIG. 14A is a sketch of an alternative implementation of a light pipe. Although the embodiments described thus far have pertained to a light pipe constructed from two main optical structures (e.g., prisms, for example the first optical structure **P1** and the second optical structure **P2**) having indices of refraction that are different from each other, other embodiments are possible in which a single main optical structure (i.e., block, in the current figure the first optical structure **P1**) is used in conjunction with, for example, an array of microprisms **1360** deployed at the output surface **S12** of the block. The current figure illustrates such an embodiment, in which the light pipe remains in a single main block (**P1**) and the direction of the radiated light **L31** at the block output can be adjusted via an array of microprisms **1360** at the block output. The array of microprisms **1360** can be used to change direction of the radiated light **L31** to be non-normal to the surface **S12.** Alternatively, the same or similar functionality can be achieved by deploying a commercially available Direction Turning Films (DTF) at the block output **S12**.

FIG. 14B is a sketch of a variation of the embodiment illustrated in FIG. 14A. In the current figure, the diffuser **1360** is deployed at the output of the array of microprisms **1360**. The diffuser **1350** has the effect of further spreading the light that is output by the microprism array so as to cover a wider range of angles **L32**, and/or improve color mixing. The diffuser **1350** can be used to achieve a range of angles around a central ray (of the output rays L31), shown as the angles **L32.**

14B, the diffuser **1350** of FIG. 14C spreads the light **L32** that is output by the additional optical structure **1312** in order to cover a wider range of angles, and/or improve color mixing.

FIG. 15A is a sketch of a side view 1500 and a top view 1502 of the light pipe of FIG. 13C to FIG. 13I. The current figures, at least in part, define the dimensions of the outcoupling wedge (additional optical structure **1312**) to avoid loss of light from the single base optical structure **1310** to be output from the new output surface **1308**. "Y" is the minimum length of the out coupling wedge (along an edge from the single base optical structure to the output surface) , "h" is the height of the single base optical structure **1310**, "Z" is the length of the lightpipe from the input to output surface, "a" is an angle at which an incoming ray reflects off the side of the lightpipe to intersect where the extension of the wedge meets an other surface of the lightpipe, "H" is the height of the out coupled ray (from the edge of the wedge / additional optical structure **1312** to the output surface) , "V" is the height of the wedge beyond the light pipe base optical structure **1310**, and "θ" is the angle of the wedge between the output surface and a surface of the base optical structure **1310**.

"$Y = h \tan a Z$" is the minimum length of the out coupling wedge (the additional optical structure **1312**) to avoid loss of propagating light rays in the lightpipe **1500** by TIR.

"$H = h + [V/[1+[\tan \theta / \tan a]]]$" where "H" is the minimum height of the out coupling wedge (the additional optical structure **1312**).

A typical ratio to allow sufficient color mixing is "$5 < [Z / h] < 10$".

FIG. 16A is a sketch of a conventional folded light pipe **1600** using a reflective coating **1606** (i.e., mirror coating) to achieve re-direction of the light path of input light **1602** to output light **1603**. In the current configuration, light can be lost during propagation through the light pipe **1600** via at least two light ray arrangements, for example, input light **1604** couples out as lost output light **1605** and input light **1608** couples out (escapes) as lost output light **1609**.

Note, for clarity in the current and next figures, refraction of the light path is not shown.

FIG. 16B is a sketch of an improved light pipe **1610**. In the current embodiment, an interface **1620** is configured between the first optical structure **P1** and a fourth optical structure **P4**, and also configured between the fourth optical structure **P4** and the second optical structure **P2**. The fourth optical structure **P4** has a mirrored internal surface **1606** configured on a side of the fourth optical structure **P4** other than the sides adjoining the first **P1** and second **P2** optical

FIG. 16B is a sketch of an improved light pipe **1610**. In the current embodiment, an interface **1620** is configured between the first optical structure **P1** and a fourth optical structure **P4**, and also configured between the fourth optical structure **P4** and the second optical structure **P2**. The fourth optical structure **P4** has a mirrored internal surface **1606** configured on a side of the fourth optical structure **P4** other than the sides adjoining the first **P1** and second **P2** optical structures. A typical interface **1620** is using a low index optical cement. This low index interface(s) **1620** allows low angles (with respect to normal of the surface) of propagating light rays to pass through the interface **1620**, and high angles of propagating light rays will be reflected by TIR.

The interface **1620** (each interface, shown as exemplary interface **1620A** and **1620B**) at least in part generates TIR **1616** (shown as respective exemplary TIR **1616A** and **1616B**) and avoids light loss. In the current figure, the interface **1620** results in TIR at area **1616**. The propagating input light **1604** undergoes TIR **1616B** at the interface **1620B**, the light continues through the second optical structure **P2**, and exits the output surface of the light pipe **1610** as output light **1615**. The propagating input light **1608** undergoes TIR **1616A** at the interface **1620A**, the light continues through the second optical structure **P2**, and exits the output surface of the light pipe **1610** as output light **1619**. Thus, the two ray arrangements (input light **1604** and **1608**) that are lost in a conventional implementation (FIG. 16A, **1605**, **1609**) are preserved (**1615**, **1619**) using the current embodiment of additional low index interfaces **1620**).

In an alternative embodiment, the interface(s) **1620** can be implemented with (an) air gap(s). In the current figure, in a non-limiting implementation, the input surface **S01** and output surface **S23** are tilted in the opposite direction (for example, orthogonal) relative to the tilt of the mirror **1606**. As described above, the tilt of the input surface S**01** can be described using the eleventh angle (ψ) and the tilt of the output surface S**23** can be described using the eighth angle (γ).

FIG. 16C is a sketch of the improved light pipe **1610** of FIG. 16B, but sketched in three-dimensions (3D) and with alternative tilt and rotation of the input and output surfaces. In the current embodiment of a light pipe **1630**, the input surface **S01** and output surface **S23** are tilted in the same direction (for example, parallel) relative to the tilt of the mirror **1606**. As described above, the input **S01** and output **S23** surfaces can be tilted at any angle relative to the light pipe **600** axis. Preferably, the input **S01** and output **S23** surfaces are tilted between 0° (zero) and 45°, and most preferably tilted at 45°. The input surfaces can also lack tilt, that is be straight, as described above for example in reference to FIG. 2A light pipe **600A** and FIG. 3 light pipe **600C**.

In addition, in the current embodiment, the input surface **S01** and output surface **S23** are rotated. The input surface **S01** is rotated, as shown by arrows **1601**, relative to the (first) longitudinal axis **R1** of the first optical structure **P1**. Similarly, the output surface **S23** is rotated, as shown by arrows **1623**, relative to the second longitudinal axis **R2** of the second optical structure **P2**. The input **S01** and output **S23** surfaces can be rotated at any angle relative to the light pipe **600** axis. Preferably, the input **S01** and output **S23** surfaces are rotated to increments of 90° (0°, 90°, 180°, 270°).

Based on the current description, one skilled in the art will be able to select and design a refractive index of the interface **1620** (for example, selecting an optical cement with an appropriate refractive index) that is close enough to the refractive indices of the optical structures (**P1**, **P2**) to avoid rays being reflected backward (toward the input surface) by TIR, but sufficiently different (far enough) from the refractive indices of the optical structures (**P1**, **P2**) to implement sufficient TIR to avoid light escaping from the sides of the light pipe **600**.

Note that the rotating described in reference to the current figure's lightpipe **1630** can be applied to all of the above-described light pipes **600**.

Note that the above-described examples, numbers used, and exemplary calculations are to assist in the description of this embodiment. Inadvertent typographical errors, mathematical errors, and/or the use of simplified calculations do not detract from the utility and basic advantages of the invention.

To the extent that the appended claims have been drafted without multiple dependencies, this has been done only to accommodate formal requirements in jurisdictions that do not allow such multiple dependencies. Note that all possible combinations of features that would be implied by rendering the claims multiply dependent are explicitly envisaged and should be considered part of the invention.

The descriptions of the various embodiments of the present disclosure have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

As used herein, the singular form “a”, “an” and “the” include plural references unless the context clearly dictates otherwise.

The word “exemplary” is used herein to mean “serving as an example, instance or illustration”. Any embodiment described as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments and/or to exclude the incorporation of features from other embodiments.

It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable subcombination or as suitable in any other described embodiment of the invention. Certain features described in the context of various embodiments are not to be considered essential features of those embodiments, unless the embodiment is inoperative without those elements.

WHAT IS CLAIMED IS:

1. An apparatus comprising:

a light pipe (**600**) including at least:

(i) a first optical structure (**P1**) having a first refractive index (η_1), an input surface (**S01**) at a proximal end of said lightpipe (**600**), and a second surface (**S12**), and

(ii) a second optical structure (**P2**) having a second refractive index (η_2) not equal to said first refractive index, a third surface (**S21**), and an output surface (**S23**) at a distal end of said lightpipe (**600**),

said light pipe (**600**) having a longitudinal axis (**R1**) parallel to a long dimension (**606**) of said first optical structure (**P1**) in a direction between said input surface (**S01**), and said second surface (**S12**), and

an interface (**620**) between said second surface (**S12**) and said third surface (**S21**) being oblique to said longitudinal axis (**R1**) of said light pipe (**600**) such that an input light ray (**L0**) to said input surface (**S01**) injected parallel to said longitudinal axis (**R1**) is output from said output surface (**S23**) as an output light ray (**L3**) non-parallel to said input light ray (**L0**).

2. The apparatus of claim 1 wherein an angle between said input light ray (**L0**) and said output light ray (**L3**) is an optical angle of deviation of said light pipe (**600**), said optical angle of deviation being other than zero degrees (0°).

3. The apparatus of claim 1 wherein an angle between said longitudinal axis (**R1**) and an output surface normal (**R23**) is a mechanical angle of deviation of said light pipe (**600**), said mechanical angle of deviation being other than zero degrees (0°), said output surface normal (**R23**) being normal to said output surface (**S23**) of said second optical structure (**P2**).

4. The apparatus of claim 1 wherein at least said first (**P1**) and second (**P2**) optical structures define an optical path of light through said light pipe (**600**), said optical path defined at least in part by the light:

(a) coupling-in via said input surface (**S01**),

(b) traversing said first optical structure (**P1**),

(c) refracting from said first (**P1**) to said second (**P2**) optical structures via said interface (**620**) from said second (**S12**) to said third (**S21**) surfaces,
(d) traversing said second optical structure (**P2**), and
(e) coupling out of said second optical structure (**P2**) via said output surface (**S23**).

5. The apparatus of claim 4 wherein at least one outer sidewall (**S14**, **S15**, **S24**, **S25**) of said first (**P1**) and second (**P2**) optical structures is coated with a reflective coating, said reflective coating constraining said optical path within said light pipe (**600**).

6. The apparatus of claim 1 wherein an anti-reflective coating is added to at least one surface (**S01**, **S12**, **S21**, **S23**) of said at least first (**P1**) and second (**P2**) optical structures.

7. The apparatus of claim 1 wherein said second surface (**S12**) adjoins said third surface (**S21**).

8. The apparatus of claim 1 wherein said second surface (**S12**) is separated from said third surface (**S21**) by a gap (**660**, **670**).

9. The apparatus of claim 8 wherein said gap filled with a material selected from the group consisting of:
(a) air,
(b) optical cement, and
(c) optical gel.

10. The apparatus of claim 8 wherein said third surface (**S21**) is configured at a gap angle (**1000**) relative to said second surface (**S12**).

11. The apparatus of claim 8 wherein said first optical structure (**P1**) has a first width (**W1**) and said second optical structure (**P2**) has a fifth width (**W23**), said fifth width (**W23**), greater than said first width (**W1**).

12. The apparatus of claim 1 wherein a third width (**W11**) of said first optical structure (**P1**) and/or a fourth width (**W22**) of said second optical structure (**P2**) varies along the longitudinal axis (**R1**) of said light pipe (**600**).

13. The apparatus of claim 1 wherein said output surface (**S23**) is at an eighth angle (γ, “gamma”) and/or said input surface (**S01**) is at an eleventh angle (ψ, “psi”) relative to said longitudinal axis (**R1**) of said light pipe (**600**).

14. The apparatus of claim 1 further including a light source (**610**) providing input light (**L0**, **L7**) to said input surface (**S01**) of said light pipe (**600**).

15. The apparatus of claim 1 further including projecting optics (**612**), said light pipe (**600**) configured to provide said output ray (**L3**) as an input to said projecting optics (**612**).

16. The apparatus of claim 1 wherein, said long dimension (**606**) of said light pipe (**600**) is at least an order of magnitude larger than said light pipe (**600**) width (**W1**, **W11**, **W2**, **W22**).

17. An apparatus comprising:

a light pipe (**600**) including at least:

(i) a first optical structure (**P1**) having a first refractive index (η_1), an input surface (**S01**) at a proximal end of said lightpipe (**600**), and a second surface (**S12**), and

(ii) a second optical structure (**P2**) having said first refractive index (η_1), a third surface (**S21**), and an output surface (**S23**) at a distal end of said lightpipe (**600**),

said light pipe (**600**) having a longitudinal axis (**R1**) parallel to a long dimension (**606**) of said first optical structure (**P1**) in a direction between said input surface (**S01**), and said second surface (**S12**), and

an interface (**620**) between said second surface (**S12**) and said third surface (**S21**) being oblique to said longitudinal axis (**R1**) of said light pipe (**600**) such that an input light ray (**L0**) to said input surface (**S01**) injected parallel to said longitudinal axis (**R1**) is output from said output surface (**S23**) as an output light ray (**L3**) non-parallel to said input light ray (**L0**), wherein said second surface (**S12**) is separated from said third surface (**S21**) by a gap (**660**, **670**).

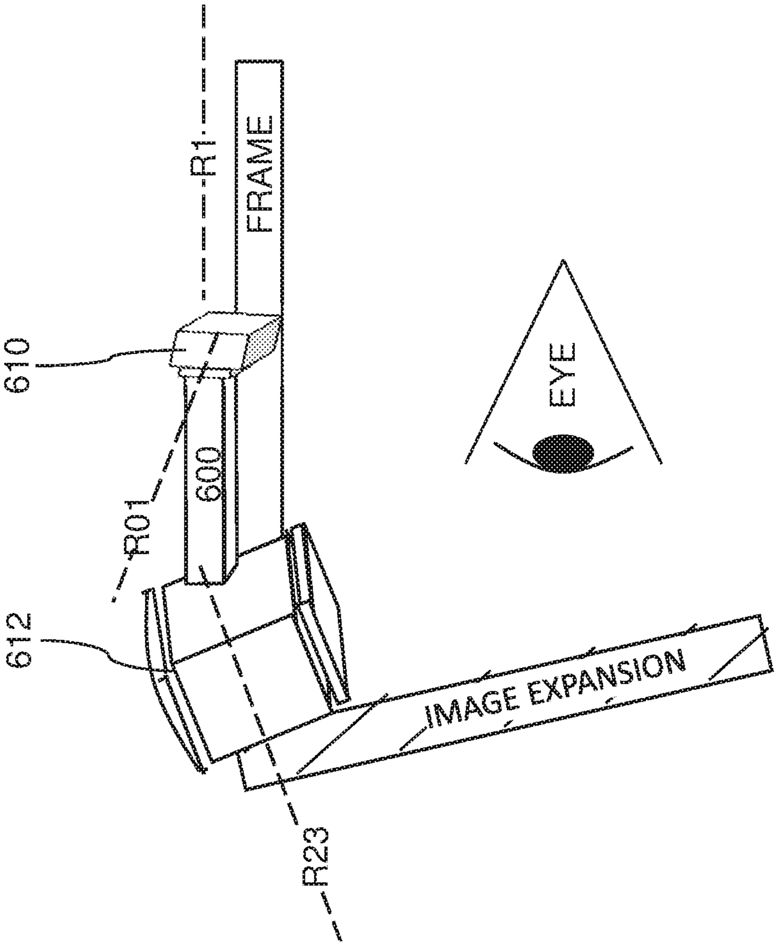


FIG. 1

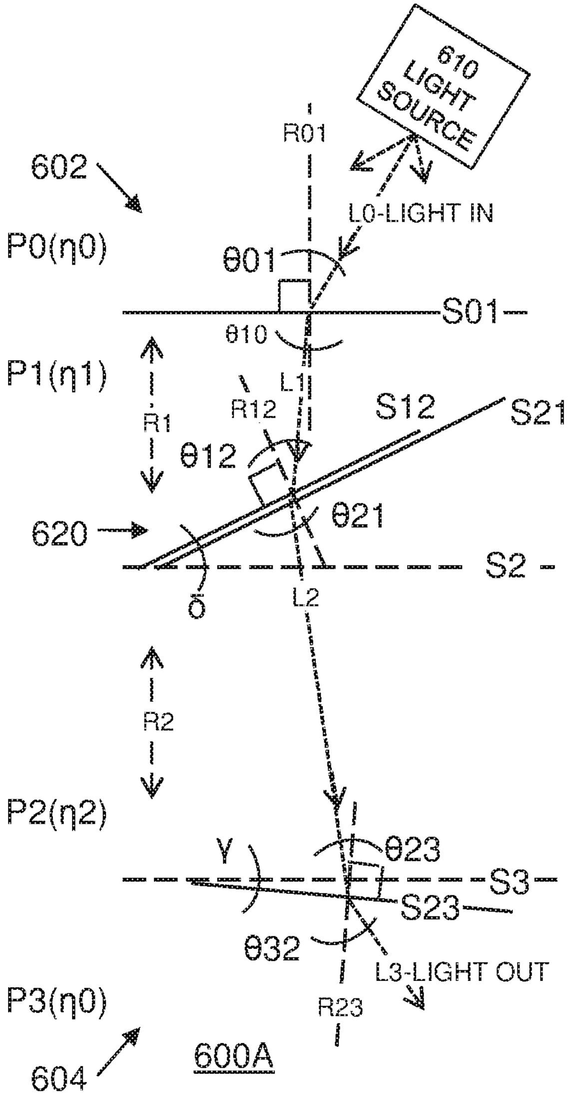

610
LIGHT
SOURCE
R01
L0-LIGHT IN
602
P0(η0)
θ01
S01
θ10
P1(η1)
L1
R12
S12
S21
R1
θ12
θ21
620
S2
δ
L2
R2
P2(η2)
γ
θ23
S3
S23
θ32
L3-LIGHT OUT
R23
P3(η0)
604
600A

FIG. 2A

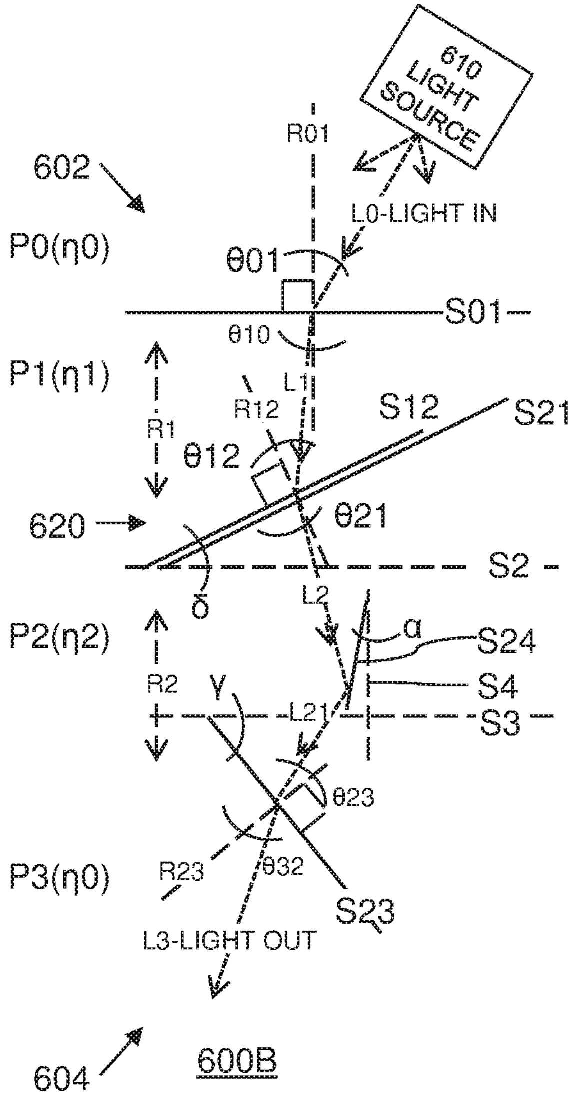

610
LIGHT
SOURCE
R01
L0-LIGHT IN
602
P0(η0)
θ01
S01
θ10
P1(η1)
L1
R12
S12
S21
R1
θ12
θ21
620
S2
δ
L2
α
S24
P2(η2)
R2
γ
S4
L21
S3
θ23
R23
θ32
P3(η0)
S23
L3-LIGHT OUT
604
600B

FIG. 2B

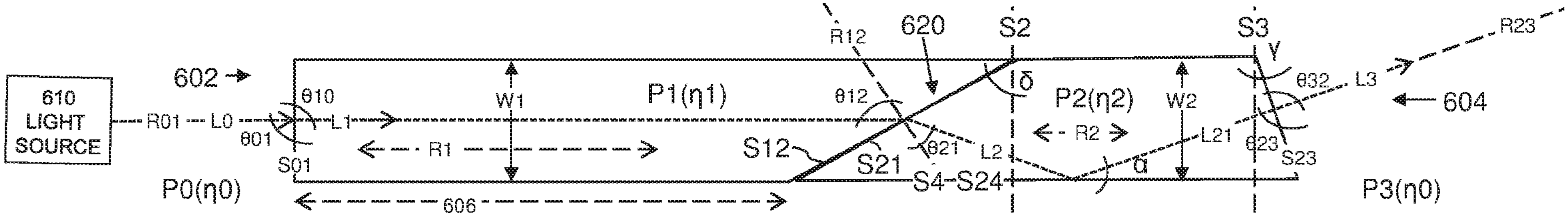


FIG. 3

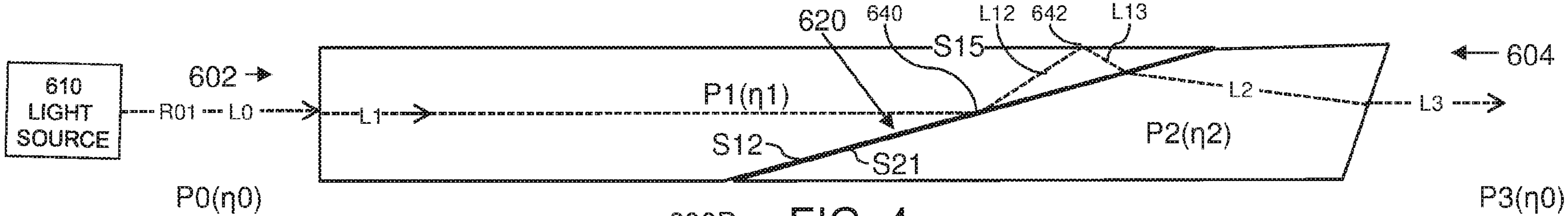


FIG. 4

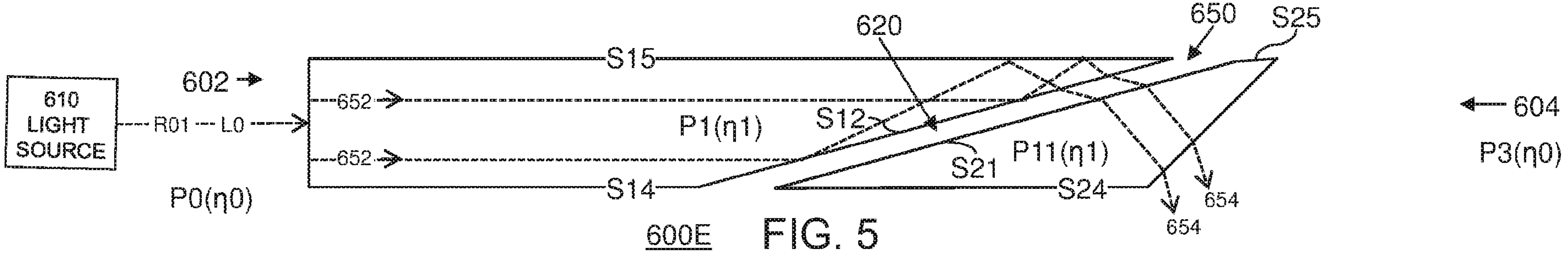


FIG. 5

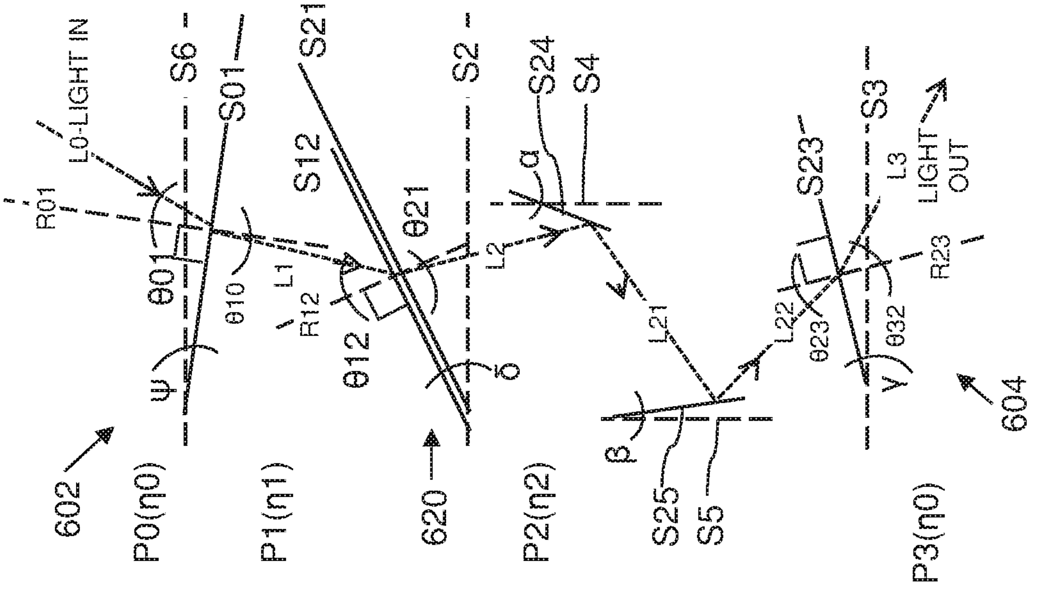


FIG. 8

600G

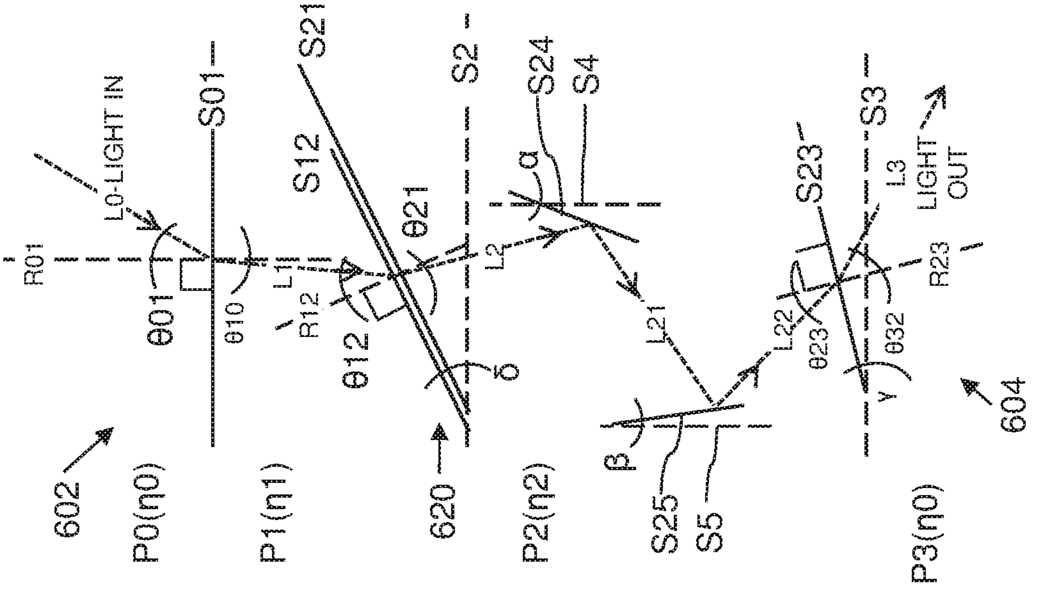
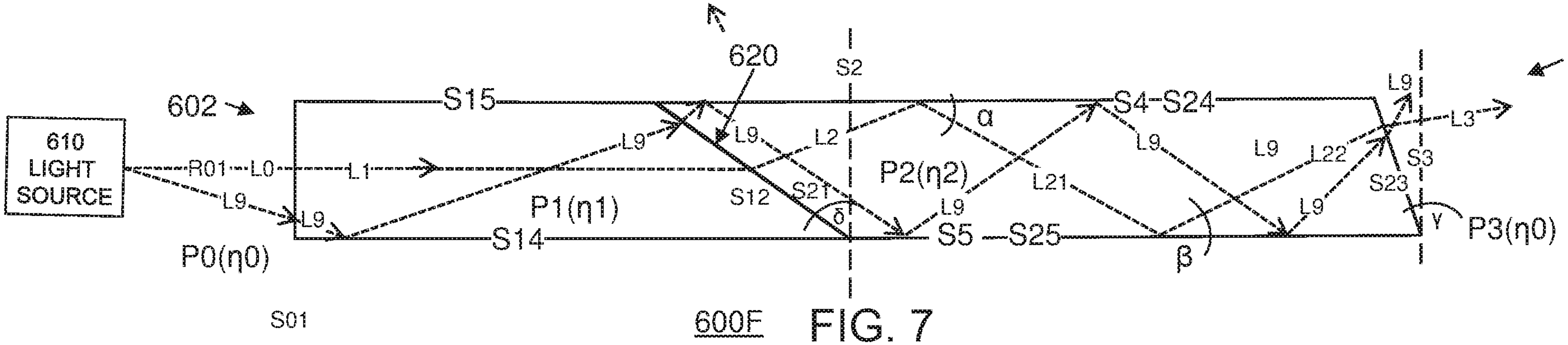
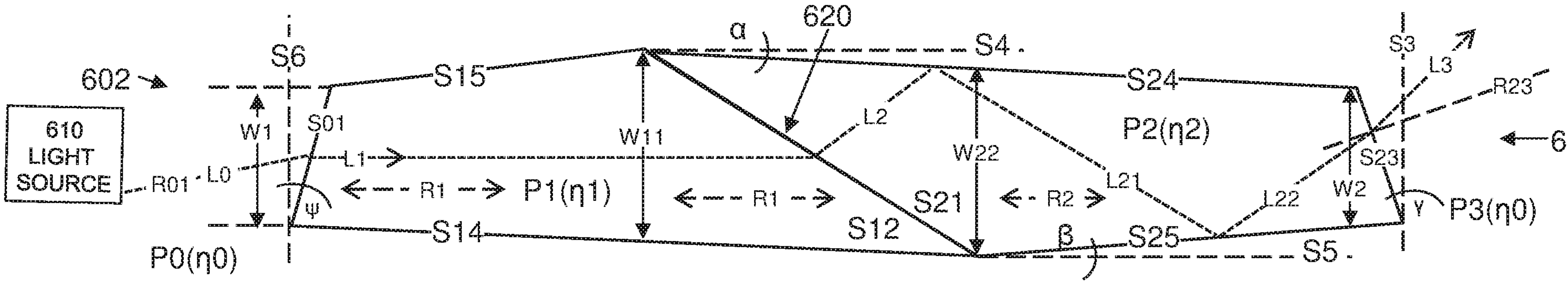


FIG. 6

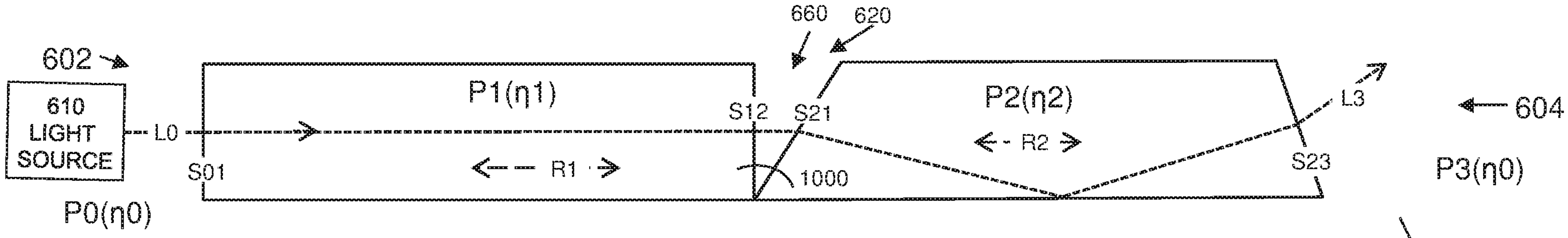
600F



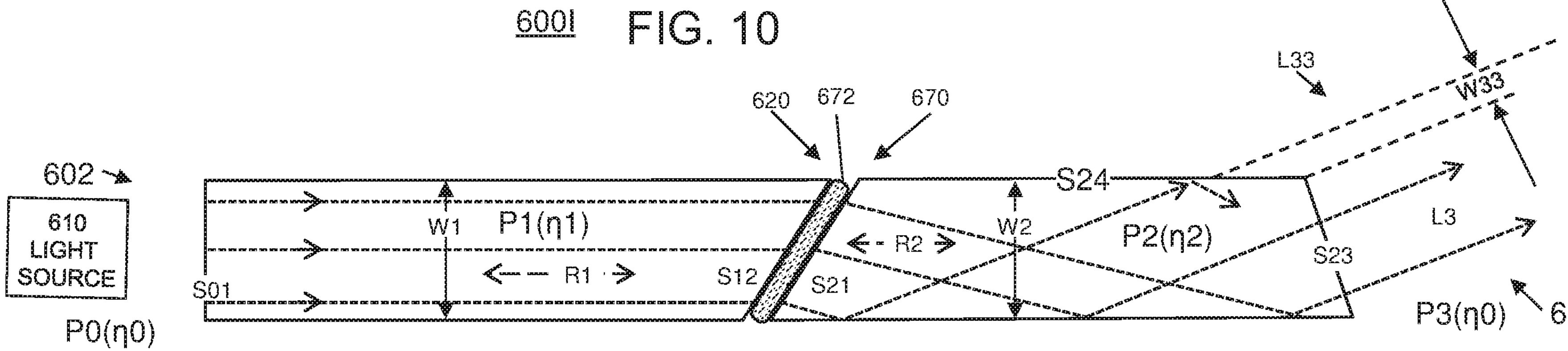
600F FIG. 7



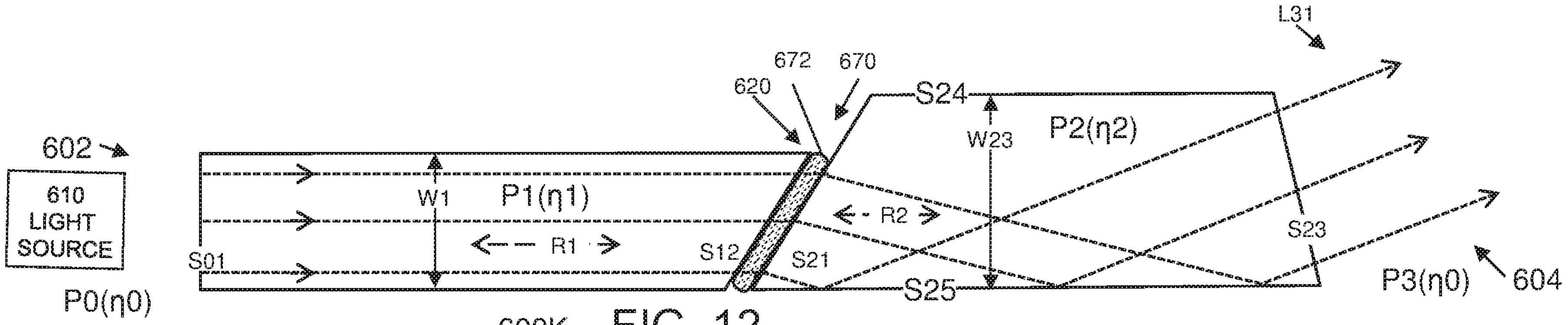
600G FIG. 9



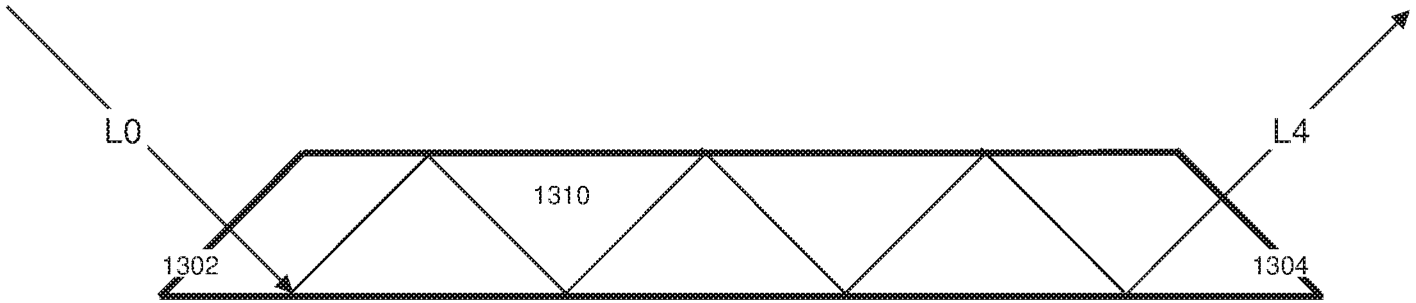
600I FIG. 10



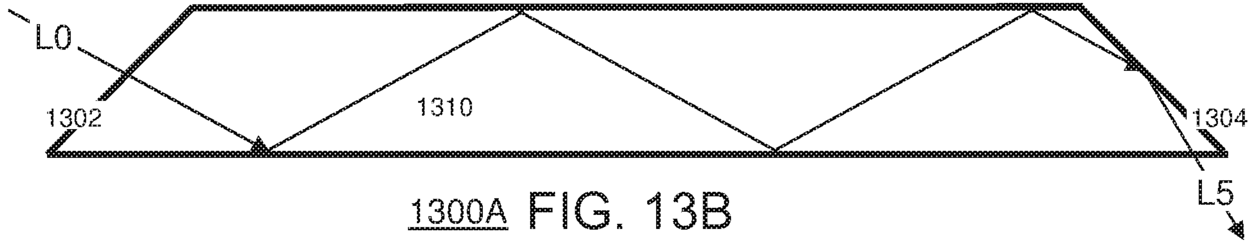
600J FIG. 11



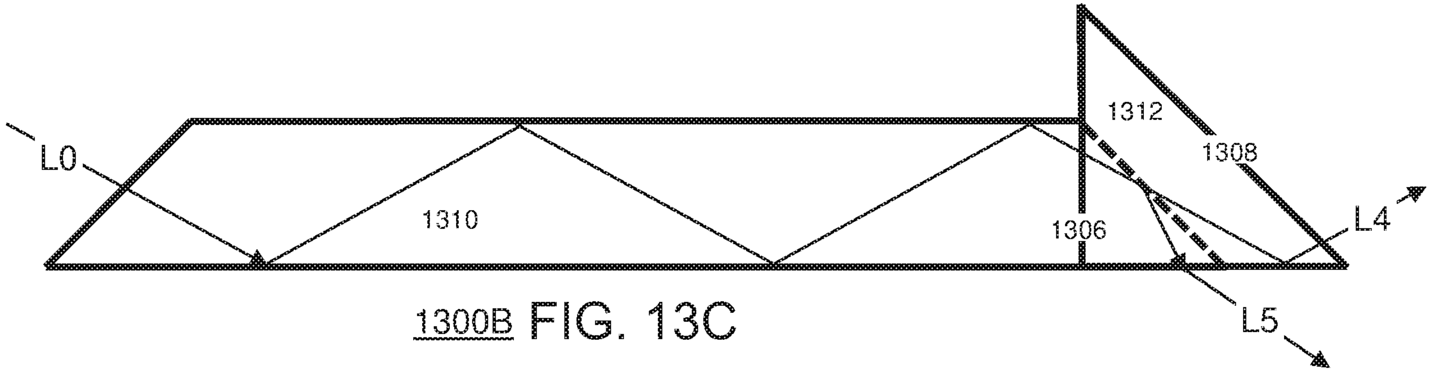
600K FIG. 12



1300A FIG. 13A



1300A FIG. 13B



1300B FIG. 13C

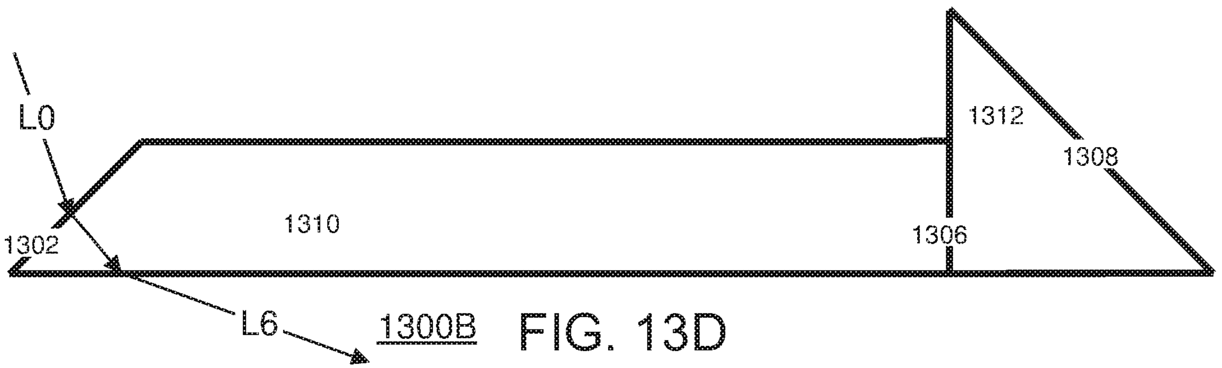


FIG. 13D

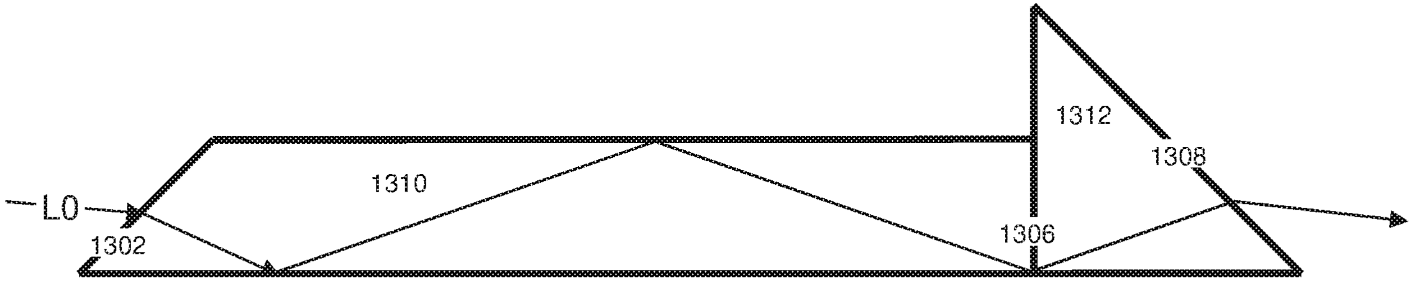


FIG. 13E

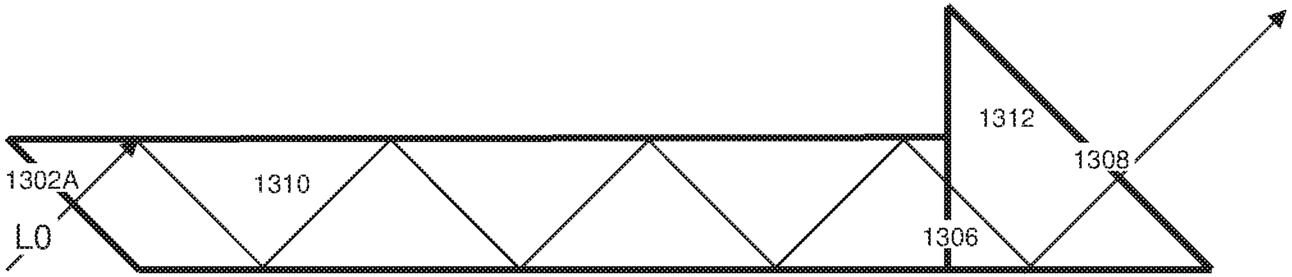
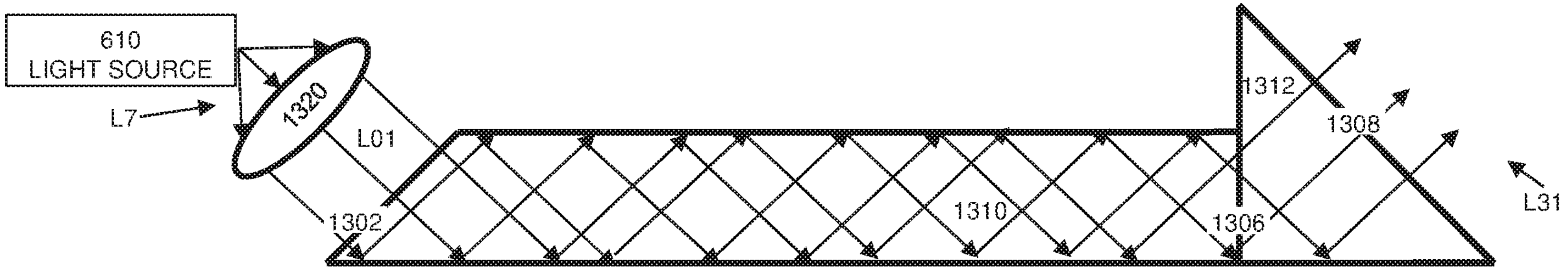
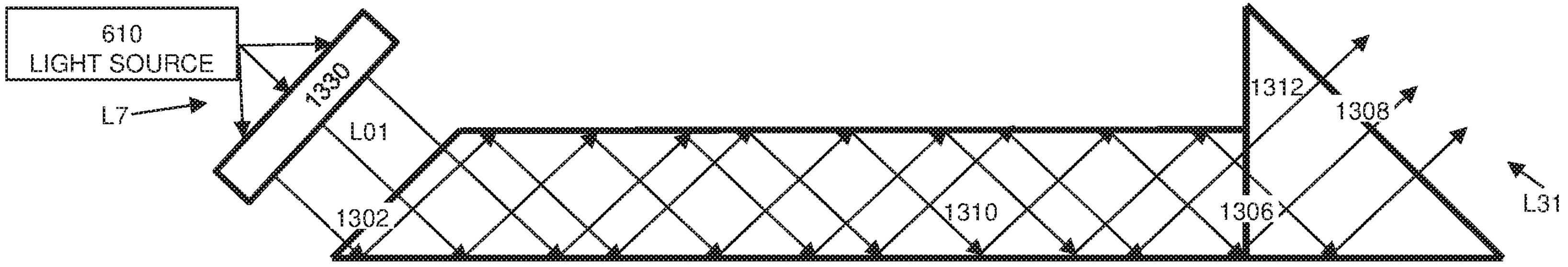


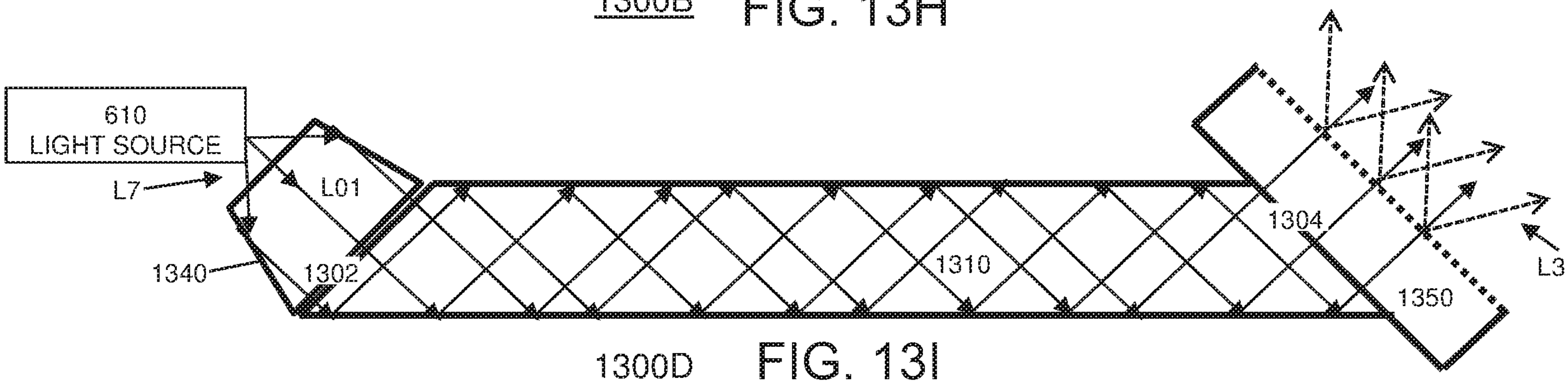
FIG. 13F



1300B FIG. 13G



1300B FIG. 13H



1300D FIG. 13I

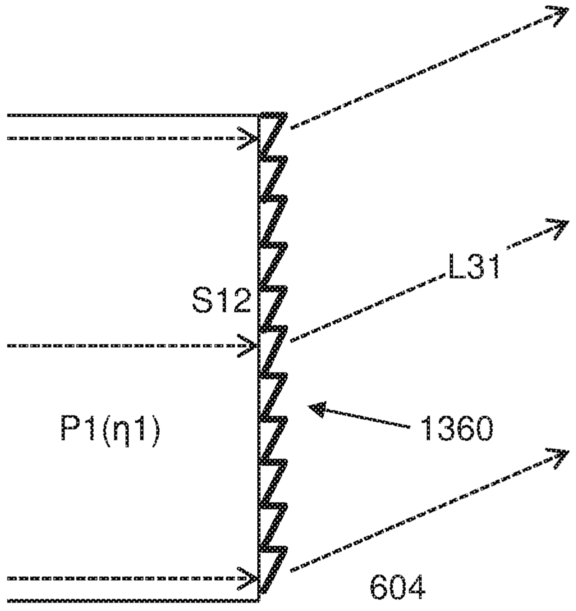


FIG. 14A

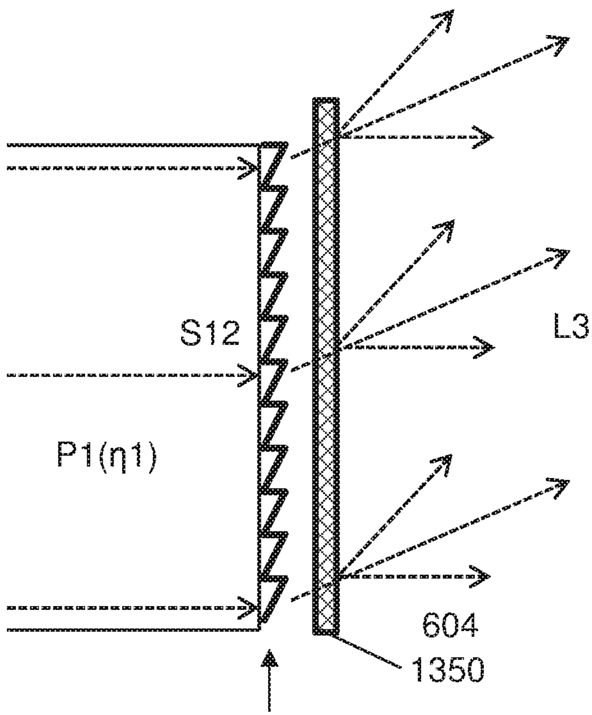


FIG. 14B

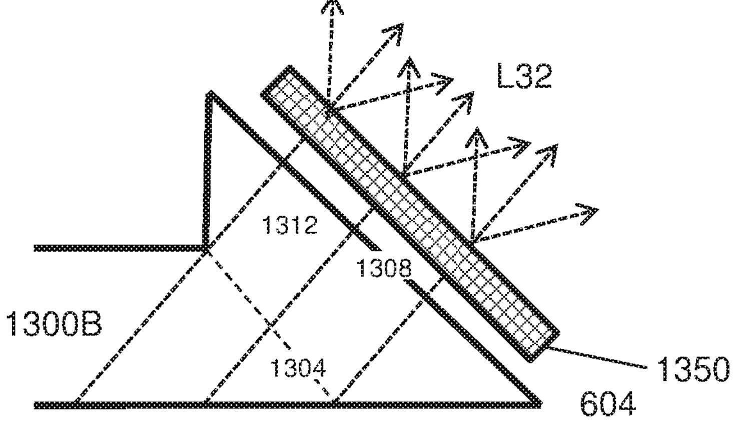


FIG. 14C

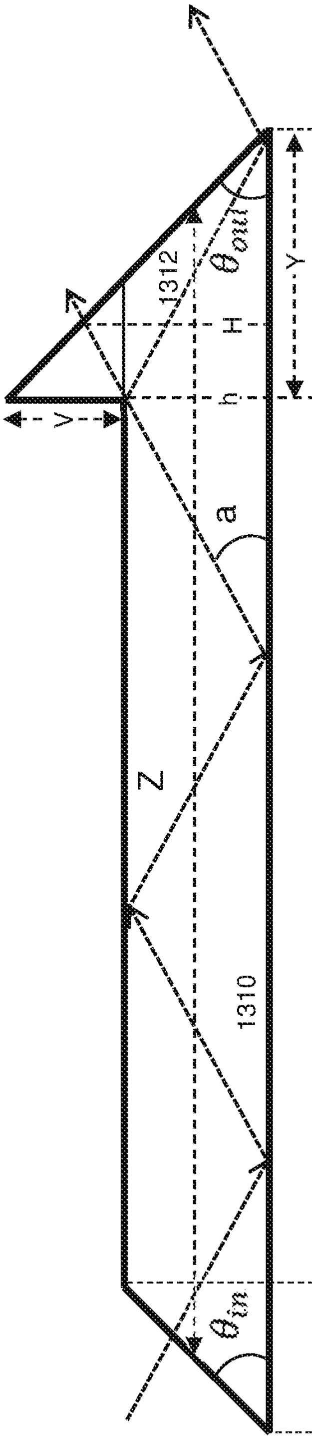


FIG. 15A

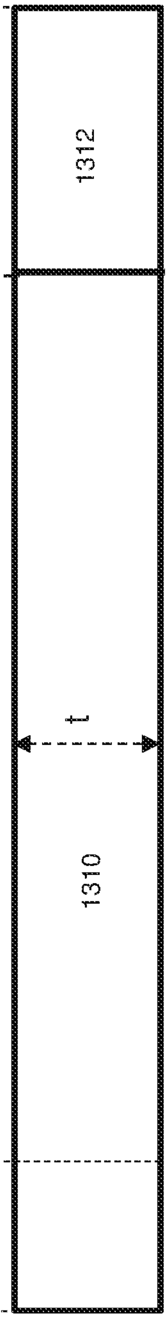
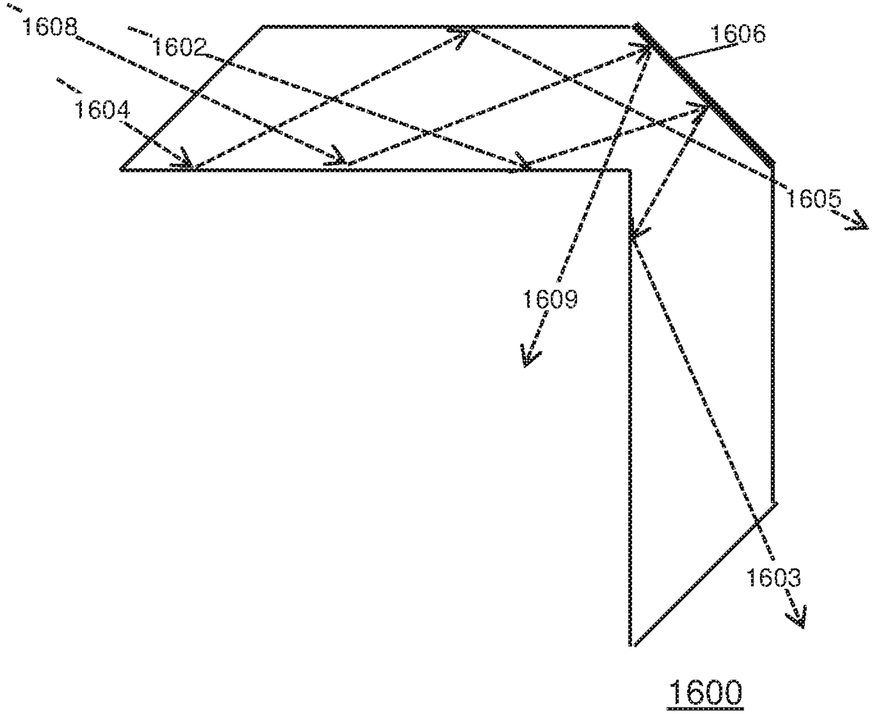


FIG. 15B



PRIOR ART

FIG. 16A

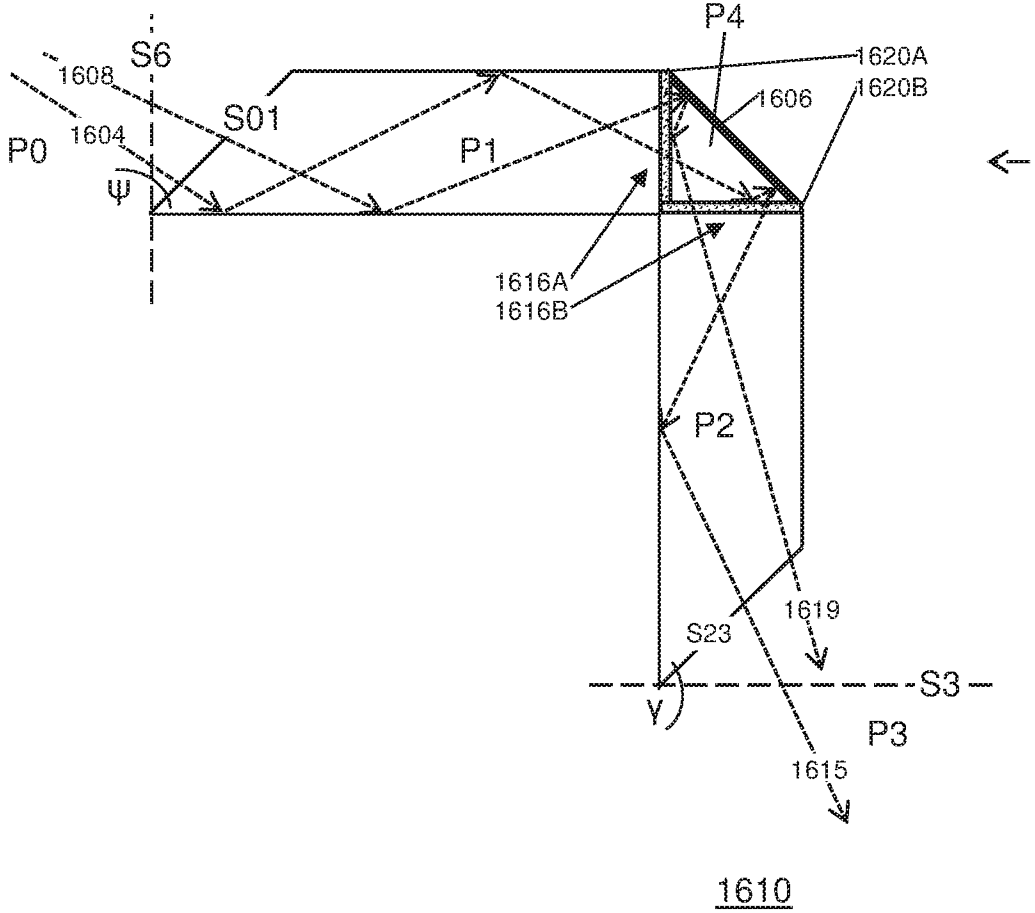


FIG. 16B

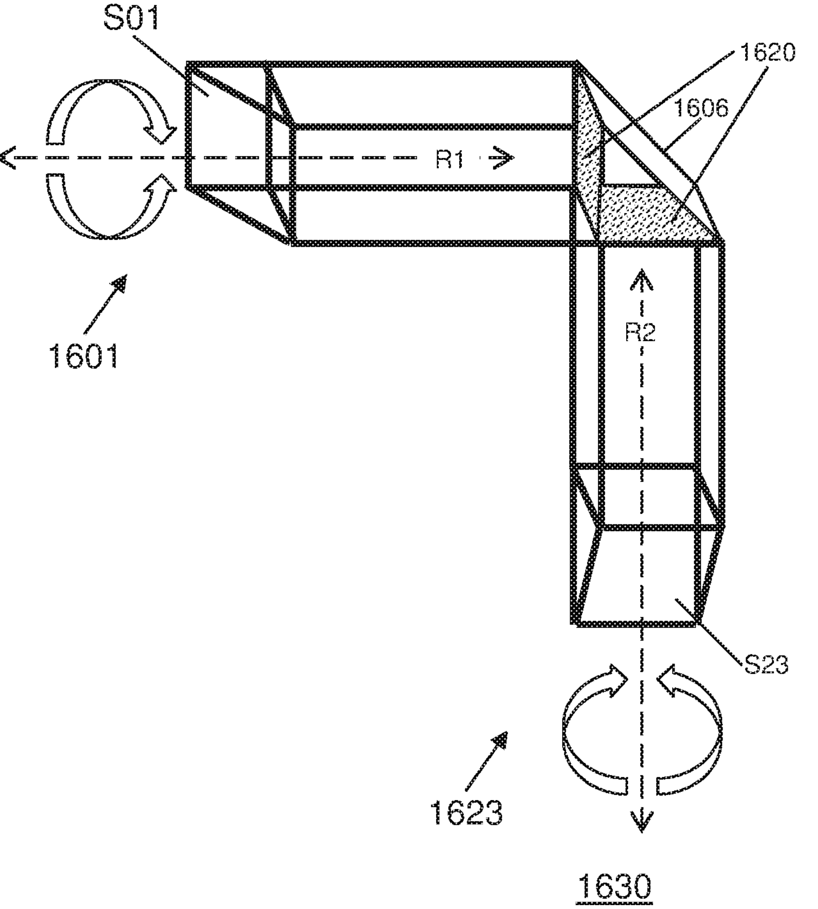


FIG. 16C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2020/051005

A. CLASSIFICATION OF SUBJECT MATTER
See extra sheet.

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)
IPC (20200101) G02B 26/08, G02B 27/01, F21V 8/00, G02B 6/42
CPC (20130101) G02B 26/0875, G02B 26/0883, G02B 26/0891, G02B 27/0172, G02B 6/0053, G02B 6/0011, G02B 6/0061, G02B 6/4212

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)
Databases consulted: Google Patents, Google Scholar, Orbit, SIMILARI
Search terms used: light pipe; light tube; light guide;refraction; refraction index; second; cascade; oblique; surface; double prism; two-part; bending ; wedge; prism; Risley prism; coupling out

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2017045664 A1 CHUNG et al. 16 Feb 2017 (2017/02/16) The entire document	1-5,7,12-16
Y	The entire document	8-11,17
X	US 5905837 A WANG et al. 18 May 1999 (1999/05/18) Abstract; Fig.1 ; col.3 ll. 55-67, col.4 ll.1-23	1,2,5,6,13,16
X	US 2017242249 A1 WALL et al. 24 Aug 2017 (2017/08/24) Abstract; Figs 9A, 9B, 9C ; paragraphs 58-65	1,2,13
Y	US 5852693 A JEONG 22 Dec 1998 (1998/12/22) The entire document	8-11,17

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"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)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"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
"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
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 03 Jan 2021	Date of mailing of the international search report 05 Jan 2021
Name and mailing address of the ISA: Israel Patent Office Technology Park, Bldg.5, Malcha, Jerusalem, 9695101, Israel Email address: pctoffice@justice.gov.il	Authorized officer ABRAMOVICH Saar Telephone No. 972-73-3927203

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	LYNCH et al. "BEAM MANIPULATION: PRISMS VS. MIRRORS". Photonik International pp45-47. Mar. 2009. Available since 20 Sept. 2016 at the following URL: <http://www.edmundoptics.com/globalassets/resources/articles/beammanipulation-prisms-vs-mirrors-en.pdf> LYNCH et al. 31 Mar 2009 (2009/03/31) Abstract; first column of p.45 , middle column of p. 46; Fig. 8	17
Y	Abstract; first column of p.45 , middle column of p. 46; Fig. 8	10
A	US 2008025667 A1 AMITAI 31 Jan 2008 (2008/01/31) Abstract, paragraph 105; Fig. 32	11
A	US 2016116744 A1 TAKEDA et al. 28 Apr 2016 (2016/04/28) The entire document	1-17
A	US 2016116744 A1 TAKEDA et al. 28 Apr 2016 (2016/04/28) The entire document	1-17

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IL2020/051005

Patent document cited search report	Publication date	Patent family member(s)	Publication Date
US 2017045664 A1	16 Feb 2017	US 2017045664 A1	16 Feb 2017
		US 10007046 B2	26 Jun 2018
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