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(54) Title: CUBE POLARIZER

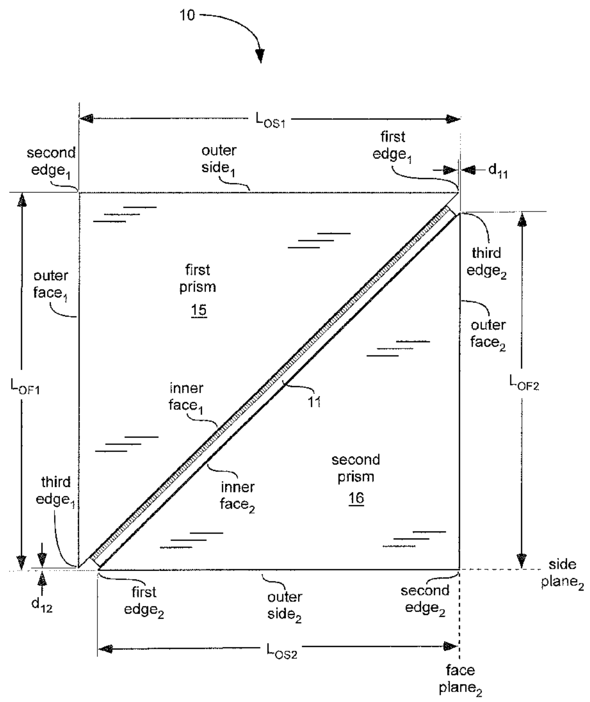

Fig. 1

(57) Abstract: Cube polarizers (10, 40, 80) designed for substantially equal optical path lengths of a reflected beam (R) and a transmitted beam (T). Cube polarizers designed to reduce wire grid polarizer curvature in order to minimize wavefront distortion of the reflected beam and the transmitted beam.

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Cube Polarizer

FIELD OF THE INVENTION

The present application is related generally to polarizing beam splitters, especially wire grid polarizers disposed inside of a cube.

BACKGROUND

Wire grid polarizers can be fastened inside of a cube. A cube polarizer can be better than a plate polarizer to (1) reduce astigmatism; (2) provide a mechanical structure, which can allow attachment of other devices (e.g. other polarizers or an LCOS imager); and (3) reduce wavefront distortion.

As shown in FIG. 13, a cube polarizer 130 can include a wire grid polarizer 131 sandwiched between two prisms - $prism_A$ 135 and $prism_B$ 136. The wire grid polarizer 131 can include wires 131_w disposed over a substrate 131_s. The cube polarizer 130 is not drawn to scale. In one example of a cube polarizer, the cube can be 10 millimeters (mm) wide, the substrate 131_s can be 0.7 mm thick, and the wires 131_w can be about 0.0003 mm thick. Thus, in order to show all components of the cube polarizer 130, the drawings have not been drawn to scale.

An unpolarized light beam U can enter one side (outer $face_A$) of $prism_A$ 135 and can be polarized into a reflected beam R and a transmitted beam T. The reflected beam R can reflect off the wires 131_w of the wire grid polarizer 131, continue through $prism_A$ 135, and exit through another side (outer $side_A$) of $prism_A$ 135. The transmitted beam T can transmit through the polarizer 131 and $prism_B$ 136, and exit through a side (outer $face_B$) of $prism_B$ 136.

The reflected beam R has an optical path length OPL_R and the transmitted beam T has an optical path length OPL_T. The optical path length OPL is defined as the actual physical distance the light travels through the cube polarizer times an index of refraction n of the material(s) through which the light travels.

In some cube polarizer designs, there is a substantial difference in optical path length between the reflected and transmitted beams due to a thickness t of the substrate 131_s (see FIGs. 13 and 14). For example, both prisms 135 and 136 can have the same size, and can be combined such that edges 137 of the prisms

135 and 136 align with edges of the wire grid polarizer 131. The wire grid polarizer 131 can be disposed at a 45° angle between the prisms 135 and 136, such that light entering perpendicularly to the outer $face_A$ will meet the wire grid polarizer 131 at a 45° angle. The wire grid polarizer 131 can have wires 131_w on one face of the wire grid polarizer 131. This cube may be physically symmetric based on outer dimensions, but not optically symmetrical due to the effect of the thickness t of the substrate 131_s. Following are calculations showing this lack of optical symmetry. See reference variables in FIGs. 13 and 14 and definitions below. Note that FIG. 14 shows only the substrate 131_s of the wire grid polarizer 131 without the wires 131_w.

1. $d_4^2 = t^2 + t^2$. $d_4 = \sqrt{2} * t$.
2. $OPL_R = d_1 * n_p + d_3 * n_p - \frac{d_4 * n_p}{2}$.
3. $OPL_R = d_1 * n_p + d_2 * n_p - \frac{t * n_p}{\sqrt{2}}$. ($d_2 = d_3$ and $d_4 = \sqrt{2} * t$)
4. $OPL_T = d_1 * n_p + d_2 * n_p - \sqrt{2} * t * n_p + \sqrt{2} * t * n_s$.
5. $\Delta OPL = |OPL_T - OPL_R| = -\sqrt{2} * t * n_p + \sqrt{2} * t * n_s + \frac{t * n_p}{\sqrt{2}} = \frac{t*(2*n_s - n_p)}{\sqrt{2}}$.
6. If $n_s = n_p$, then $\Delta OPL = \frac{t * n_p}{\sqrt{2}}$.

Reference variable definitions:

- d_1 is a distance from the outer $face_A$ to a center of the polarizer 131.
- d_2 is a distance from the outer $face_B$ to a center of the polarizer 131.
- d_3 is a distance from where the light is polarized to the outer $side_A$. Due to structural symmetry of the cube, d_2 can equal d_3.
- d_4 is a distance of travel of the transmitted beam 104 through the polarizer 131.
- n_p is an index of refraction of the prisms (assuming both prisms have the same index).
- n_s is an index of refraction of the substrate. Any thin films on the substrate 131_s are ignored as they are negligible relative to a thickness of the substrate 131_s.
- t is a thickness of the substrate. t is also a third leg of a triangle formed by d_4 and t for a light beam U meeting the polarizer at a 45° angle.

- ΔOPL is an absolute difference in optical path length between the transmitted beam T and the reflected beam R.

This difference in optical path length $\Delta OPL = \frac{t*n_p}{\sqrt{2}}$ can cause problems in some applications. Methods have been proposed to solve such problems, some of which may be impractical due to high manufacturing cost.

Curvature of a wire grid polarizer 131 in a cube can cause problems. The wire grid polarizer can curve due to stresses induced by the wires or other thin films adjacent to the wires. This curvature can result in a reflected light beam reflected off of one region of the polarizer having a different optical path length than a reflected light beam reflected off of another region of the polarizer, thus causing wavefront distortion. There can be a similar problem with the transmitted beam.

Information relevant to wire grid polarizers and polarizing cubes can be found in U.S. Patent Numbers US 8,467,128; US 7,570,424; US 7,085,050; US 6,288,840; U.S. Patent Publication Number 2007/0297052; and in the publication "A new type of beam splitting polarizer cube," Meadowlark Optics, Thomas Baur, 2005, pages 1-9.

SUMMARY

It has been recognized that it would be advantageous to have a cube polarizer with minimal difference in optical path length between reflected and transmitted beams. It has been recognized that it would be advantageous to have a cube polarizer with flat wire grid polarizer and minimal wavefront distortion. The present invention is directed to various embodiments of cube polarizers that satisfy these needs. Each embodiment may satisfy one or both of these needs.

In one embodiment, the cube polarizer can comprise a first prism and a second prism. The first prism can include two triangular faces linked by an inner face (inner $face_1$), an outer face (outer $face_1$), and an outer side (outer $side_1$). There can be a junction of the inner $face_1$ and the outer $side_1$ defining a first edge (first $edge_1$). The second prism can include two triangular faces linked by an inner face (inner $face_2$), an outer face (outer $face_2$), and an outer side (outer $side_2$). The cube polarizer can comprise a wire grid polarizer. The wire grid

polarizer can include a substrate having a first surface and an opposite second surface substantially parallel to the first surface. An array of parallel, elongated, separated wires can be disposed over the first surface of the substrate. The wire grid polarizer can be sandwiched between the first prism and the second prism such that: (1) the second surface of the substrate is attached to and faces the inner $face_2$; (2) the wires are attached to and face the inner $face_1$; the outer $face_1$ is opposite to the outer $face_2$; and the outer $side_1$ is opposite to the outer $side_2$. A plane of the outer $face_2$ (face $plane_2$) can be substantially aligned with the first $edge_1$.

In another embodiment, the cube polarizer can comprise a first prism and a second prism. The first prism can include two triangular faces linked by an inner face (inner $face_1$), an outer face (outer $face_1$), and an outer side (outer $side_1$). The second prism can include two triangular faces linked by an inner face (inner $face_2$), an outer face (outer $face_2$), and an outer side (outer $side_2$). The cube polarizer can comprise a wire grid polarizer. The wire grid polarizer can include an array of parallel, elongated, separated wires sandwiched between a first substrate and a second substrate. Each substrate can have a thickness of greater than 0.4 millimeters. The wire grid polarizer can be sandwiched between the inner faces of the prisms.

In another embodiment, a cube polarizer can be designed for polarization of light including a wavelength λ. The cube polarizer can comprise a first prism, a second prism, and a wire grid polarizer sandwiched between inner faces of the prisms. The wire grid polarizer can include a substrate having a first surface and an opposite second surface substantially parallel to the first surface. There can be a material ($material_1$) disposed over the first surface of the substrate. The $material_1$ can include an array of parallel, elongated, separated wires. There can be a thin film (thin $film_2$) disposed over the second surface. The thin $film_2$ can include a material and a thickness to reduce a curvature of the first surface in order to minimize wavefront distortion.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic side view of a cube polarizer, with a closely aligned first $edge_1$ and face $plane_2$, in accordance with an embodiment of the present invention;

FIG. 2 is a schematic side view of the cube polarizer of FIG. 1, showing an unpolarized beam, a reflected beam, and a transmitted beam, in accordance with an embodiment of the present invention;

FIG. 3 is a schematic perspective view of a first prism and a second prism of the cube polarizer of FIG. 1;

FIG. 4 is a schematic side view of a cube polarizer, including a wire grid polarizer with wires sandwiched between a first substrate and a second substrate, in accordance with an embodiment of the present invention;

FIGs. 5-6 are detailed, schematic, side-views of corners of the cube polarizer of FIG. 4, in accordance with embodiments of the present invention;

FIG. 7 is a schematic side view of the cube polarizer of FIG. 4, showing an unpolarized beam, a reflected beam, and a transmitted beam, in accordance with an embodiment of the present invention;

FIG. 8 is a schematic side view of a cube polarizer, with a wire grid polarizer having a thin film disposed over a back side of the substrate in order to flatten the wire grid polarizer, in accordance with an embodiment of the present invention;

FIGs. 9-12 are schematic cross-sectional side views of portions of wire grid polarizers, in accordance with embodiments of the present invention;

FIG. 13 is a schematic side view of a cube polarizer, in accordance with the prior art; and

FIG. 14 is a schematic cross-sectional side view of a portion of a substrate of a wire grid polarizer, in accordance with the prior art.

DEFINITIONS

As used herein, "cube" means a solid that is bounded by six faces. Each face need not be square, rectangle, or parallelogram. At least one of the faces can have a curved surface, such as a parabolic shape for example.

As used herein, the term "light" can mean light or electromagnetic radiation in the x-ray, ultraviolet, visible, and/or infrared, or other regions of the electromagnetic spectrum.

As used herein "thin film" means a substantially continuous or unbroken film of material having a thickness not larger than three times a maximum wavelength in the light spectrum of interest. "Substantially continuous" in this definition means that there may be some discontinuity, such as pinholes, but no major discontinuity, such as a division into a grid or separate wires.

DETAILED DESCRIPTION

Various cube polarizer and wire grid polarizer designs will be described and shown in the figures. These cube polarizers and wire grid polarizers are not necessarily drawn to scale. Due to a relatively large size of prisms of the cubes, smaller size of wire grid polarizer substrates, and very small size of wires or thin films, it would be impractical to draw to scale. Some dimensions of these components are specified below and others are known in the art.

As illustrated in FIGs. 1 and 2, a cube polarizer 10 is shown comprising a first prism 15 and a second prism 16. This cube polarizer 10 can be designed for equal, or nearly equal, optical path lengths of a reflected beam R and a transmitted beam T of light. It has been recognized that it can be important to keep these two optical path lengths as close to equal as possible. Examples of applications which require equal (or near equal) optical path lengths are interferometry and 3D projection displays.

The first prism 15 can include two triangular faces linked by an inner face (inner $face_1$), an outer face (outer $face_1$), and an outer side (outer $side_1$). A junction of the inner $face_1$ and the outer $side_1$ defines a first edge (first $edge_1$). A junction of the outer $face_1$ and the outer $side_1$ defines a second edge (second $edge_1$). A junction of the inner $face_1$ and the outer $face_1$ defines a third edge (third $edge_1$). A distance from the first $edge_1$ to the second $edge_1$ defines an outer side length (L_{OS1}). A distance from the second $edge_1$ to the third $edge_1$ defines an outer face $length_1$ (L_{OF1}).

The second prism 16 can include two triangular faces linked by an inner face (inner $face_2$), an outer face (outer $face_2$), and an outer side (outer $side_2$). A junction of the inner $face_2$ and the outer $side_2$ defines a first edge (first $edge_2$). A junction of the outer $face_2$ and the outer $side_2$ defines a second edge (second $edge_2$). A junction of the inner $face_2$ and the outer $face_2$ defines a third edge (third $edge_2$). A distance from the first $edge_2$ to the second $edge_2$ defines an outer side $length_2$ (L_{OS2}). A distance from the second $edge_2$ to the third $edge_2$ defines an outer face $length_2$ (L_{OF2}).

The cube polarizer 10 can include a wire grid polarizer 11. The wire grid polarizer can be made according to one of the various embodiments of wire grid polarizers 90, 41, 110, and 120 shown in FIGs. 9-12. The wire grid polarizer 11 can include a substrate 92 having a first surface 92_f and an opposite second surface 92_s substantially parallel to the first surface 92_f. An array of parallel, elongated, separated wires 91 (separated by gaps G) can be disposed over the first surface 92_f of the substrate 92. The wire grid polarizer 11 can be sandwiched between the first prism 15 and the second prism 16 such that: (1) the second surface 92_s of the substrate 92 is attached to and faces the inner $face_2$; (2) the wires 91 are attached to and face the inner $face_1$; (3) the outer $face_1$ is opposite to the outer $face_2$; (4) and the outer $side_1$ is opposite to the outer $side_2$.

An unpolarized light beam U can enter through the outer $face_1$. The unpolarized light beam U can be polarized at the wire grid polarizer 11, forming (1) a transmitted beam T of light transmitting through the wire grid polarizer 11 and exiting through the outer $face_2$; and (2) a reflected beam R of light reflecting off of the wire grid polarizer 11 and exiting through the outer $side_1$. The cube polarizer 10 can be designed for equal, or nearly equal, optical path lengths of the reflected beam R and the transmitted beam T. Optical path length is a distance of light travel through a material times an index of refraction of the material.

One way of equalizing, or nearly equalizing, the optical path lengths of the reflected beam R and the transmitted beam T is to align a plane (face $plane_2$) of the outer $face_2$ with the first $edge_1$. Exact alignment can be optimal, but considerable benefit can be gained by substantial alignment. Imperfections in manufacturing may make exact alignment too difficult. This alignment can be quantified by a distance d_{11} between the face $plane_2$ and the first $edge_1$. For exact alignment, $d_{11} = 0$. Substantial alignment can be $d_{11} < 500$ micrometers in one aspect, $d_{11} < 100$ micrometers in another aspect, or $d_{11} < 10$ micrometers in another aspect. Such alignment can equalize, or nearly equalize, optical path lengths of the reflected beam R and the transmitted beam T.

This alignment can be done by shifting the second prism 16 down and to the left (based on view of FIGs. 1-2) or by decreasing L_{OS2} relative to L_{OS1}. L_{OS1} minus L_{OS2} can be between 500 micrometers and 1000 micrometers in one aspect. The actual desired difference between L_{OS1} and L_{OS2} can depend on a thickness t of the substrate 92.

In some designs, it can be desirable to have $L_{OS1} > L_{OS2}$ and $L_{OF1} > L_{OF2}$. Having $L_{OS1} > L_{OS2}$ and $L_{OF1} > L_{OF2}$ may be desirable to form a square end of the cube polarizer 10 where the triangular faces of the prisms 15 and 16 join, to allow the cube polarizer 10 to fit into a structure where the cube polarizer 10 will be used, or to avoid an edge of a prism sticking out beyond the rest of the cube where it could be damaged. Having $L_{OS1} > L_{OS2}$ and $L_{OF1} > L_{OF2}$ may be desirable if the cube polarizer 10 is designed to allow unpolarized light to enter through the outer $side_1$ and it is important for reflected and transmitted beams from this light to also have equal, or nearly equal optical path lengths.

Thus, in addition to aligning the face $plane_2$ with the first $edge_1$, a plane (side $plane_2$) of the outer $side_2$ can be substantially aligned with the third $edge_1$, thus minimizing a distance d_{12} between the side $plane_2$ and the third $edge_1$. d_{12} can be less than 500 micrometers in one aspect, less than 100 micrometers in another aspect, or less than 10 micrometers in another aspect. L_{OF1} minus L_{OF2} can be between 500 micrometers and 1000 micrometers in one aspect. The actual desired difference between L_{OF1} and L_{OF2} can depend on a thickness t of the substrate 92.

By minimizing the distances d_{11} and/or d_{12}, optical path lengths of the reflected beam R and the transmitted beam T can be equal or substantially equal. Thus, the cube polarizer 10 can satisfy the equation $|OPL_T - OPL_R| < \frac{0.5*t*n_p}{\sqrt{2}}$ in one aspect, can satisfy the equation $|OPL_T - OPL_R| < \frac{0.1*t*n_p}{\sqrt{2}}$ in another aspect, can satisfy the equation $|OPL_T - OPL_R| < \frac{0.01*t*n_p}{\sqrt{2}}$ in another aspect, or can satisfy the equation $|OPL_T - OPL_R| < \frac{0.001*t*n_p}{\sqrt{2}}$ in another aspect, wherein:

- OPL_T is an optical path length of the transmitted beam T;
- OPL_R is an optical path length of the reflected beam R;
- t is a thickness of the substrate 92 between the first surface 92_f and the second surface 92_s; and
- n_p is an index of refraction of the first prism 15.

$|OPL_T - OPL_R|$ can be less than 500 micrometers in one aspect, less than 100 micrometers in another aspect, less than 10 micrometers in another aspect, or less than 1 micrometer in another aspect.

Illustrated in FIG. 3 are a first prism 35 and a second prism 36 in schematic perspective view, to more clearly show the sides, faces, and edges of the prisms. The first prism 35 can include two triangular faces 31 and 32 linked by an inner face (inner $face_1$), an outer face (outer $face_1$), and an outer side (outer $side_1$). The second prism 36 can include two triangular faces 33 and 34 linked by an inner face (inner $face_2$), an outer face (outer $face_2$), and an outer side (outer $side_2$). These prisms 35 and 36 are applicable to all embodiments described herein.

Illustrated in FIGs. 4-7 is another embodiment of a cube polarizer 40. The cube polarizer 40 can include a wire grid polarizer 41 sandwiched between the inner faces of a first prism 45 and a second prism 46.

The first prism 45 can include two triangular faces linked by an inner face (inner $face_1$), an outer face (outer $face_1$), and an outer side (outer $side_1$). A junction of the inner $face_1$ and the outer $side_1$ defines a first edge (first $edge_1$). A junction of the inner $face_1$ and the outer $face_1$ defines a third edge (third $edge_1$).

The second prism 46 can include two triangular faces linked by an inner face (inner $face_2$), an outer face (outer $face_2$), and an outer side (outer $side_2$). A junction of the inner $face_2$ and the outer $side_2$ defines a first edge (first $edge_2$). A junction of the inner $face_2$ and the outer $face_2$ defines a third edge (third $edge_2$).

The cube polarizer 40 can be designed for equal, or nearly equal, optical path lengths of a reflected beam R and a transmitted beam T. Such equality of optical path lengths can be achieved by wire grid polarizer symmetry and prism symmetry.

For wire grid polarizer symmetry, the wire grid polarizer 41 can include an array of parallel, elongated, separated wires 91 (separated by gaps G) sandwiched between a first substrate 92 and a second substrate 104, as shown in FIGs. 10-11. The wires 91 can be added to the first substrate 92 by standard thin film deposition and patterning techniques. The second substrate 104 can be attached on top of the wires 91 by an adhesive.

The substrates 92 and 104 can be thick in an optical sense (e.g. not thin films) in order to provide structural support for the wire grid polarizer 41. A thickness th_{92} of the first substrate 92 and a thickness th_{104} of the second substrate 104 can both be greater than 0.4 millimeters in one aspect, greater than 0.5 millimeters in another aspect, or between 0.4 and 1.4 millimeters in another aspect. For wire grid polarizer symmetry, the thickness th_{92} of the first substrate 92 can equal or substantially equal the thickness th_{104} of the second substrate 104.

A wire grid polarizer 110, as shown in FIG. 11, can be used in the cube polarizer 40 instead of wire grid polarizer 41. Wire grid polarizer 110 includes a first thin film 93, such as silicon dioxide for example, disposed above the wires 91. The first thin film 93 can also be disposed in and can substantially fill the gaps G between the wires. For symmetry, a thickness th_{92} of the first substrate 92 can equal or substantially equal a combined thickness th_{104+93} of the second substrate 104 and the first thin film 93 above the wires 91. Due to the small thickness of the first thin film 93, however, its thickness might be ignored, and a cube polarizer designer might only consider thicknesses th_{92} and th_{104} of the substrates 92 and 104. Wire grid polarizers 90 and 120, as shown in FIGs. 9 and 12, can also be used in cube polarizer 80, with the addition of a second substrate 104.

For prism symmetry, a size of the two triangular faces of the first prism 45 can equal or substantially equal a size of the two triangular faces of the second prism 46. For equal or substantially equal optical path lengths, the first prism 45 can be made of substantially the same material as the second prism 46. Alternatively, there can be differences of materials and index of refraction between the prisms, and such differences can be compensated for by differences in size between the prisms, but such a design can be complex. Symmetry of both material and size can be a simple way to obtain equivalent optical path lengths.

In addition to equal or similar prism 45 and 46 size and material, alignment of the prisms 45 and 46 can also be important for symmetry of the cube polarizer 40. The following description, and FIGs. 5 and 6, describe and show such alignment. As shown in FIG. 5, a plane of the outer $face_2$ (face $plane_2$) can cross perpendicularly a plane of the outer $side_1$ (side $plane_1$) at a first junction 42. A distance d_{14} between the first $edge_1$ and the first junction 42 can equal, or substantially equal, a distance d_{13} between the third $edge_2$ and the first junction 42. As shown in FIG. 6, a plane of the outer $face_1$ (face $plane_1$) can cross perpendicularly a plane of the outer $side_2$ (side $plane_2$) at a second junction 43. A distance d_{16} between the first $edge_2$ and the second junction 43 can equal, or substantially equal, a distance d_{15} between the third $edge_1$ and the second junction 43.

Cube symmetry, due to combined wire grid polarizer symmetry and prism symmetry, can allow equal, or substantially equal optical path lengths as described below and shown in FIG. 7. An unpolarized beam of light U, having a wavelength λ, can enter the cube polarizer 40 through the outer $face_1$ and be polarized at the wire grid polarizer 41, forming (1) a reflected beam R of light reflecting off of the wire grid polarizer 41 and exiting through the outer $side_1$ and (2) a transmitted beam T of light transmitting through the wire grid polarizer 41 and exiting through the outer $face_2$. An absolute value of a difference between an optical path length (OPL_T) of the transmitted beam T minus an optical path length (OPL_R) of the reflected beam R ($|OPL_T - OPL_R|$) can be less than 100*λ in one aspect, less than 10*λ in another aspect, less than 500 micrometers in another aspect, less than 100 micrometers in another aspect, less than 10 micrometers in another aspect, or less than 1 micrometer in another aspect. The optical path length (OPL) is a distance of light travel through a material times an index of refraction of the material.

Curvature of a wire grid polarizer in a cube can cause problems. The wire grid polarizer can curve due to stresses induced by the wires, or other thin films adjacent to the wires. This curvature can result in a reflected light beam from one region of the polarizer having a different optical path length than a reflected light beam from another region of the polarizer, thus causing wavefront distortion. There can be a similar problem with the transmitted beam.

This curvature problem can be solved or improved as shown on cube polarizer 80 and wire grid polarizer 90 in FIGs. 8 and 9 and as described below. The cube polarizer 80 can be designed for polarization of light including a wavelength λ.

The cube polarizer 80 can include a first prism 85 and a second prism 86. The first prism 85 can include two triangular faces linked by an inner face, an outer face (outer $face_1$), and an outer side (outer $side_1$). The second prism 86 can include two triangular faces linked by an inner face, an outer face (outer $face_2$), and an outer side (outer $side_2$).

A wire grid polarizer 90 can be sandwiched between the inner faces of the prisms 85 and 86. The wire grid polarizer 90 can include a substrate 92 having a first surface 92_f and an opposite second surface 92_s substantially parallel to the first surface 92_f. There can be a material ($material_1$) 96 disposed over the first surface 92_f of the substrate 92. The $material_1$ 96 can include an array of parallel, elongated, separated wires 91 (separated by gaps G). $Material_1$ 96 can also include other thin films 93 and/or 94 as will be described below. There can be a thin film (thin $film_2$) 95 disposed over the second surface 92_s. The thin $film_2$ 95 can balance stresses caused by $material_1$ 96, thus reducing curvature of the wire grid polarizer 90 and reducing wavefront distortion.

This reduced wavefront distortion can be demonstrated by minimal variation of optical path lengths of light beams, such as for example light beams 82-84. Light beams, including light beams 82-84, can enter through the outer $face_1$, can reflect off of portions of the wire grid polarizer 90 within the cube polarizer 80, then can exit through the outer $side_1$. Light beams can reflect off of all portions of the wires 91 of the wire grid polarizer 90 within the cube polarizer 80. These light beams can include (1) a light beam having a shortest optical path length (OPL_S) and (2) a light beam having a longest optical path length (OPL_L). Optical path length is a distance of light travel through a material times an index of refraction of the material. A difference between the OPL_L and the OPL_S defines a peak to valley (PTV). In other words, $|OPL_L - OPL_S| = PTV$. The thin $film_2$ 95 can include a material and a thickness to reduce a curvature of the wire grid polarizer 90 such that the PTV is less than λ/2 in one aspect, less than λ/4 in another aspect, less than λ/8 in another aspect, less than 500 nanometers in another aspect, less than 350 nanometers in another aspect, or less than 100 nanometers in another aspect.

One way for the thin $film_2$ 95 to balance stresses caused by the $material_1$ 96 is for the thin $film_2$ to include a same material as in the $material_1$ 96. For example, if the $material_1$ includes silicon dioxide, then the thin $film_2$ can also include silicon dioxide; or if the $material_1$ includes titanium dioxide, then the thin $film_2$ can also include titanium dioxide. Another way for the thin $film_2$ 95 to balance stresses caused by the $material_1$ 96 is to have similar thicknesses between the thin $film_2$ 95 and the $material_1$ 96.

Use of the thin $film_2$ 95 for reduction of wavefront distortion can also be used in cube polarizers 10 and 40. Thus, the benefits of reduced wavefront distortion can be combined with the benefits of equalizing optical path lengths of reflected and transmitted beams.

Shown in FIG. 9 is a wire grid polarizer 90 which can be used in the various cube polarizers 10, 40, and 80 described above. Specifics of this design, including materials and thicknesses, can improve overall cube polarizer performance. A first thin film 93 can fill gaps G between the wires 91 and can extend above the wires 91. The first thin film 93 can comprise silicon dioxide. The first thin film 93 can extend above the wires 91 for a thickness th_{93} of between 40 and 120 nanometers. A second thin film 94 can be disposed over the first thin film 93. The second thin film 94 can comprise titanium dioxide. The second thin film 94 can have a thickness th_{94} of between 50 and 150 nanometers. If a thin $film_2$ 95 is disposed over the second surface 92_s of the substrate, for reduced wire grid polarizer 90 curvature, then this thin $film_2$ 95 can include silicon dioxide having a thickness th_{95} of between 80 and 300 nanometers.

In some applications of cube polarizers, both the reflected beam R and the transmitted beam T are used and it may be desirable to reflect one polarization as much as possible. In other applications, it can be beneficial to suppress or absorb the reflected beam R. For example, the reflected beam R may interfere with other devices in the system where the cube polarizer is used. Shown in FIG. 12 is a wire grid polarizer 120 which can be used in the various cube polarizers 10, 40, and 80 described above. For cube polarizer 10, 40, or 80, designed to polarize light including a wavelength λ, the wires 91 can include a layer of metal 121 and a layer of a material (absorptive layer) 122 that is substantially absorptive of light having the wavelength λ. The cube polarizer 10, 40, or 80 can polarize an incoming beam of light having the wavelength λ into a first beam that is primarily reflected or absorbed by the wires 91 and a second beam that is primarily transmitted through the wires 91. At least 75% of the first beam can be absorbed by the wires in one aspect, at least 85% in another aspect, or at least 92% in another aspect.

The prisms in the cube polarizers 10, 40, and 80 described herein can be triangular prisms. The inner faces, outer sides, and outer faces of the prisms can have a parallelogram shape, can be rectangular, can be square, but need not be such shapes. The two triangular faces of each prism can be parallel or substantially parallel to each other, but such relationship is not required. The prisms and the wire grid polarizer substrates can be made of a material that is substantially transparent of the desired light wavelength band (e.g. glass for visible light). In one embodiment, the wires 91 can extend longitudinally in the direction of one triangular face to the other triangular face of each prism (into the page in the figures).

What is claimed is:

CLAIMS

1. A cube polarizer comprising:
   a. a first prism including:
      i. two triangular faces linked by an inner face (inner $face_1$), an outer face (outer $face_1$), and an outer side (outer $side_1$); and
      ii. a junction of the inner $face_1$ and the outer $side_1$ defining a first edge (first $edge_1$);
   b. a second prism including two triangular faces linked by an inner face (inner $face_2$), an outer face (outer $face_2$), and an outer side (outer $side_2$);
   c. a wire grid polarizer including:
      i. a substrate having a first surface and an opposite second surface substantially parallel to the first surface; and
      ii. an array of parallel, elongated, separated wires disposed over the first surface of the substrate;
   d. the wire grid polarizer sandwiched between the first prism and the second prism such that:
      i. the second surface of the substrate is attached to and faces the inner $face_2$ of the second prism;
      ii. the wires are attached to and face the inner $face_1$ of the first prism;
      iii. the outer $face_1$ of the first prism is opposite to the outer $face_2$ of the second prism; and
      iv. the outer $side_1$ of the first prism is opposite to the outer $side_2$ of the second prism;
   e. a plane (face $plane_2$) of the outer $face_2$ of the second prism is substantially aligned with the first $edge_1$ of the first prism such that a distance (d_{11}) between the face $plane_2$ of the outer $face_2$ of the second prism and the first $edge_1$ of the first prism is less than 500 micrometers.

2. The cube polarizer of claim 1, wherein the distance (d_{11}) between the face plane$_2$ of the outer face$_2$ of the second prism and the first edge$_1$ of the first prism is less than 100 micrometers.

3. The cube polarizer of claim 1, wherein:
   a. a beam of light entering through the outer face$_1$ of the first prism, is polarized at the wire grid polarizer, forming:
      i. a transmitted beam of light transmitting through the wire grid polarizer and exiting through the outer face$_2$ of the second prism; and
      ii. a reflected beam of light reflecting off of the wire grid polarizer and exiting through the outer side$_1$ of the first prism; and
   b. the cube polarizer satisfies the equation: $|OPL_T - OPL_R| < \frac{0.5*t*n_p}{\sqrt{2}}$; where
      i. an optical path length is a distance of light travel through a material times an index of refraction of the material;
      ii. OPL_T is an optical path length of the transmitted beam;
      iii. OPL_R is an optical path length of the reflected beam;
      iv. t is a thickness of the substrate between the first surface and the second surface of the substrate; and
      v. n_p is an index of refraction of the first prism.

4. The cube polarizer of claim 3, wherein the cube polarizer satisfies the equation: $|OPL_T - OPL_R| < \frac{0.1*t*n_p}{\sqrt{2}}$.

5. The cube polarizer of claim 1, wherein:
   a. the first prism further comprises:
      i. a junction of the outer face$_1$ of the first prism and the outer side$_1$ of the first prism defines a second edge (second edge$_1$) of the first prism;
      ii. a junction of the inner face$_1$ of the first prism and the outer face$_1$ of the first prism defines a third edge (third edge$_1$) of the first prism;

iii. a distance from the first $edge_1$ of the first prism to the second $edge_1$ of the first prism defines an outer side length (L_{OS1}) of the first prism; and

iv. a distance from the second $edge_1$ of the first prism to the third $edge_1$ of the first prism defines an outer face $length_1$ (L_{OF1}) of the first prism;

b. the second prism further comprises:

i. a junction of the inner $face_2$ of the second prism and the outer $side_2$ of the second prism defines a first edge (first $edge_2$) of the second prism;

ii. a junction of the outer $face_2$ of the second prism and the outer $side_2$ of the second prism defines a second edge (second $edge_2$) of the second prism;

iii. a junction of the inner $face_2$ of the second prism and the outer $face_2$ of the second prism defines a third edge (third $edge_2$) of the second prism;

iv. a distance from the first $edge_2$ of the second prism to the second $edge_2$ of the second prism defines an outer side $length_2$ (L_{OS2}) of the second prism; and

v. a distance from the second $edge_2$ of the second prism to the third $edge_2$ of the second prism defines an outer face $length_2$ (L_{OF2}) of the second prism;

c. the outer face $length_1$ (L_{OF1}) of the first prism is greater than the outer face $length_2$ (L_{OF2}) of the second prism, and the outer side length (L_{OS1}) of the first prism is greater than the outer side $length_2$ (L_{OS2}) of the second prism; and

d. a plane (side $plane_2$) of the outer $side_2$ of the second prism is substantially aligned with the third $edge_1$ of the first prism such that a distance (d_{12}) between the side $plane_2$ of the second plane and the third $edge_1$ of the first prism is less than 500 micrometers.

6. The cube polarizer of claim 1, wherein the distance (d_{12}) between the side $plane_2$ of the second plane and the third $edge_1$ of the first prism is less than 100 micrometers

7. The cube polarizer of claim 1, wherein a difference between the outer side length (L_{OS1}) of the first prism and the outer side $length_2$ (L_{OS2}) of the second prism is greater than 500 micrometers.

8. The cube polarizer of claim 1, wherein a difference between the outer face $length_1$ (L_{OF1}) of the first prism and the outer face $length_2$ (L_{OF2}) of the second prism is greater than 500 micrometers.

9. The cube polarizer of claim 1, further comprising:
   a. a thin film of silicon dioxide filling gaps between the wires and extending above the wires for a thickness of between 40 and 120 nanometers; and
   b. a thin film of titanium dioxide disposed over the thin film of silicon dioxide, the thin film of titanium dioxide having a thickness of between 50 and 150 nanometers.

10. The cube polarizer of claim 1, wherein:
   a. the cube polarizer is designed to polarize light including a wavelength λ;
   b. the wires include a layer of metal and a layer of a material that is substantially absorptive of light having the wavelength λ;
   c. the cube polarizer is capable of polarizing an incoming beam of light having the wavelength λ into a first beam that is primarily reflected or absorbed by the wires and a second beam that is primarily transmitted through the wires; and
   d. at least 75% of the first beam is absorbed by the wires.

11. A cube polarizer comprising:

a. a first prism including two triangular faces linked by an inner face (inner $face_1$), an outer face (outer $face_1$), and an outer side (outer $side_1$);
b. a second prism including two triangular faces linked by an inner face (inner $face_2$), an outer face (outer $face_2$), and an outer side (outer $side_2$);
c. a wire grid polarizer including an array of parallel, elongated, separated wires sandwiched between a first substrate and a second substrate;
d. a thickness of the first substrate and a thickness of the second substrate are both greater than 0.4 millimeters; and
e. the wire grid polarizer being sandwiched between the inner faces of the prisms.

12.The cube polarizer of claim 11, further comprising:
a. a thin film of silicon dioxide filling gaps between the wires and extending above the wires for a thickness of between 40 and 120 nanometers; and
b. a thin film of titanium dioxide disposed over the thin film of silicon dioxide, the thin film of titanium dioxide having a thickness of between 50 and 150 nanometers.

13.The cube polarizer of claim 11, wherein:
a. the cube polarizer is designed to polarize light including a wavelength λ;
b. the wires include a layer of metal and a layer of a material that is substantially absorptive of light having the wavelength λ;
c. the cube polarizer is capable of polarizing an incoming beam of light having the wavelength λ into a first beam that is primarily reflected or absorbed by the wires and a second beam that is primarily transmitted through the wires; and
d. at least 75% of the first beam is absorbed by the wires.

14. A cube polarizer designed for polarization of light including a wavelength λ, the cube polarizer comprising:

a. a first prism including two triangular faces linked by an inner face, an outer face (outer $face_1$), and an outer side (outer $side_1$);

b. a second prism including two triangular faces linked by an inner face, an outer face (outer $face_2$), and an outer side (outer $side_2$);

c. a wire grid polarizer including:

i. a substrate having a first surface and an opposite second surface substantially parallel to the first surface;

ii. a material ($material_1$) disposed over the first surface, the $material_1$ including an array of parallel, elongated, separated wires; and

iii. a thin film (thin $film_2$) disposed over the second surface;

d. the wire grid polarizer sandwiched between the inner faces of the prisms;

e. a distance of light travel through a material times an index of refraction of the material defining an optical path length;

f. light beams entering through the outer $face_1$ of the first prism, reflecting off of portions of the wire grid polarizer within the cube polarizer, then exiting through the outer $side_1$ of the first prism include:

i. a light beam having a shortest optical path length (OPL_S); and

ii. a light beam having a longest optical path length (OPL_L);

g. a difference between the longest optical path length (OPL_L) and the shortest optical path length (OPL_S) defines a peak to valley (PTV); and

h. the thin $film_2$ includes a material and a thickness to reduce a curvature of the wire grid polarizer such that the peak to valley (PTV) is less than half the wavelength λ.

15. The cube polarizer of claim 14, wherein the peak to valley PTV is less than a quarter of the wavelength λ.

16. The cube polarizer of claim 14, wherein the peak to valley PTV is less than 350 nanometers.

17. The cube polarizer of claim 14, wherein the thin $film_2$ includes a same material as the $material_1$ disposed over the first surface of the substrate of the wire grid polarizer.

18. The cube polarizer of claim 14, wherein the thin $film_2$ includes silicon dioxide.

19. The cube polarizer of claim 14, wherein:
   a. the $material_1$ disposed over the first surface of the substrate of the wire grid polarizer includes:
      i. a continuous thin film of silicon dioxide filling gaps between the wires and extending above the wires for a thickness of between 40 and 120 nanometers; and
      ii. a thin film of titanium dioxide disposed over the thin film of silicon dioxide, the thin film of titanium dioxide having a thickness of between 50 and 150 nanometers; and
   b. the thin $film_2$ includes silicon dioxide having a thickness of between 80 and 300 nanometers.

20. The cube polarizer of claim 14, wherein:
   a. the cube polarizer is designed to polarize light including a wavelength λ;
   b. the wires include a layer of metal and a layer of a material that is substantially absorptive of light having the wavelength λ;
   c. the cube polarizer is capable of polarizing an incoming beam of light having the wavelength λ into a first beam that is primarily reflected or absorbed by the wires and a second beam that is primarily transmitted through the wires; and
   d. at least 75% of the first beam is absorbed by the wires.

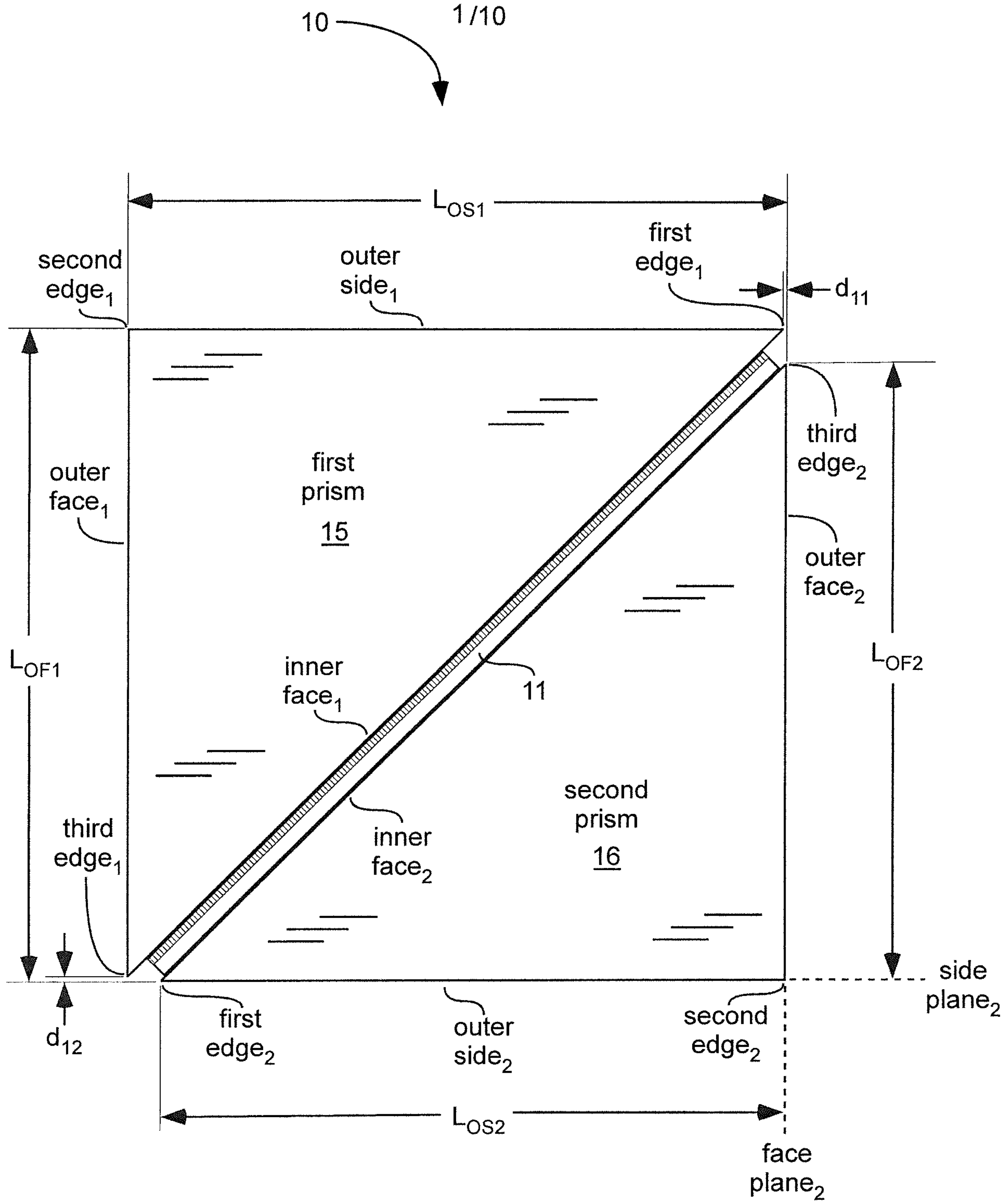

10
L_OS1
second edge_1
outer side_1
first edge_1
d_11
first prism
15
third edge_2
outer face_1
outer face_2
L_OF1
L_OF2
inner face_1
11
second prism
16
inner face_2
third edge_1
side plane_2
d_12
first edge_2
outer side_2
second edge_2
L_OS2
face plane_2

Fig. 1

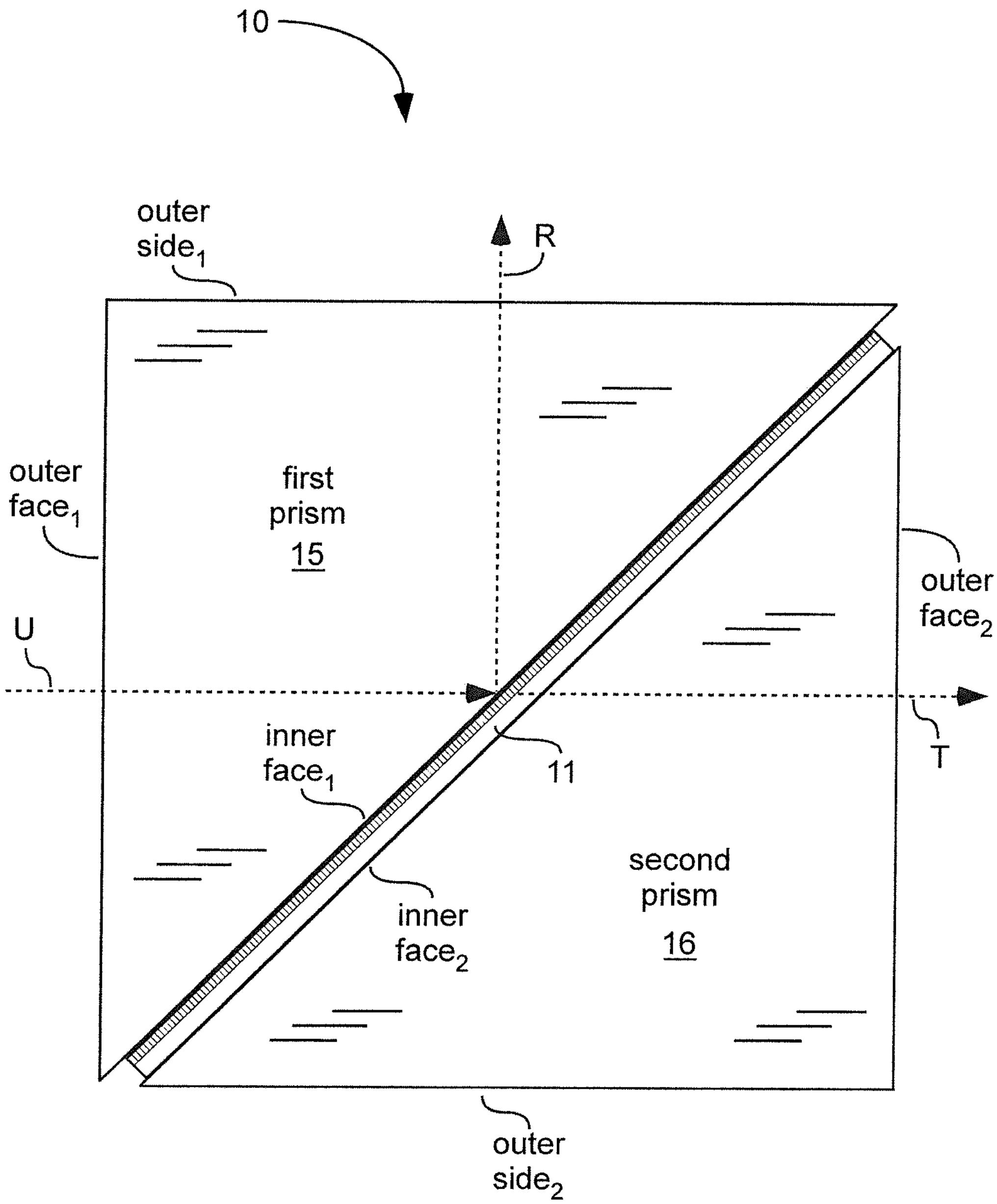

10
outer side1
R
outer face1
first prism 15
outer face2
U
T
11
inner face1
inner face2
second prism 16
outer side2

Fig. 2

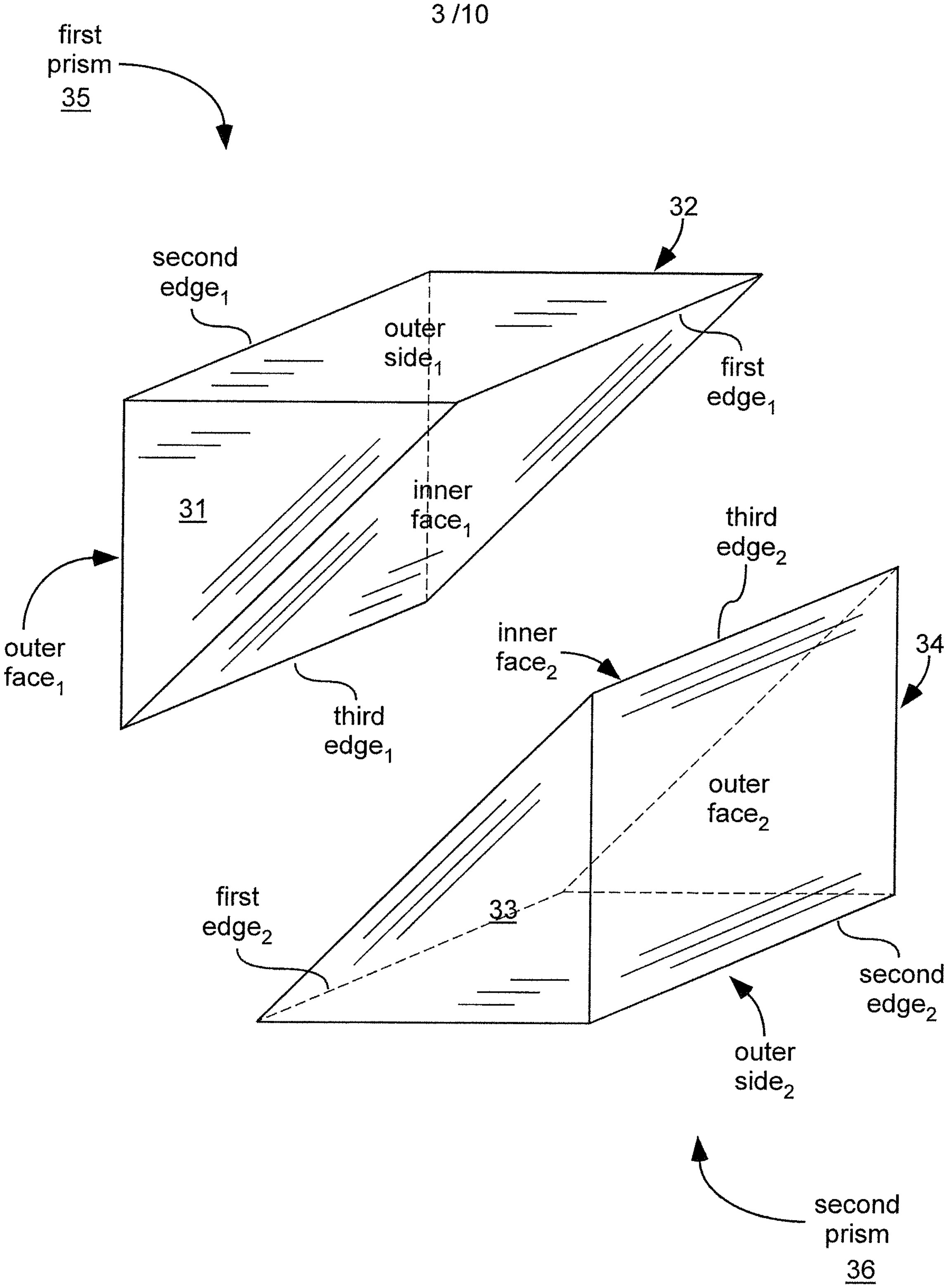

first
prism
35
32
second
edge1
outer
side1
first
edge1
31
inner
face1
third
edge2
outer
face1
inner
face2
34
third
edge1
outer
face2
first
edge2
33
second
edge2
outer
side2
second
prism
36

Fig. 3

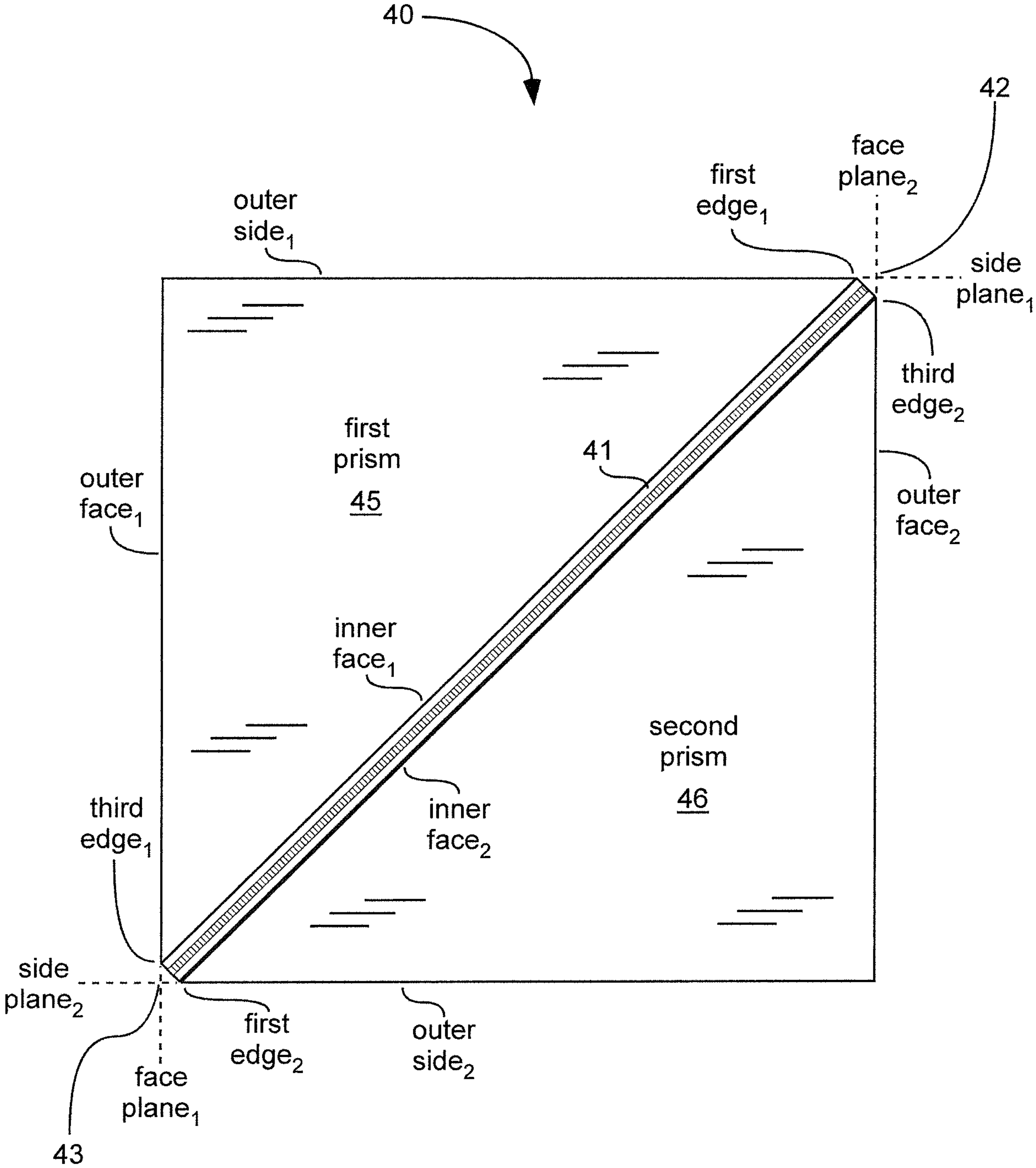
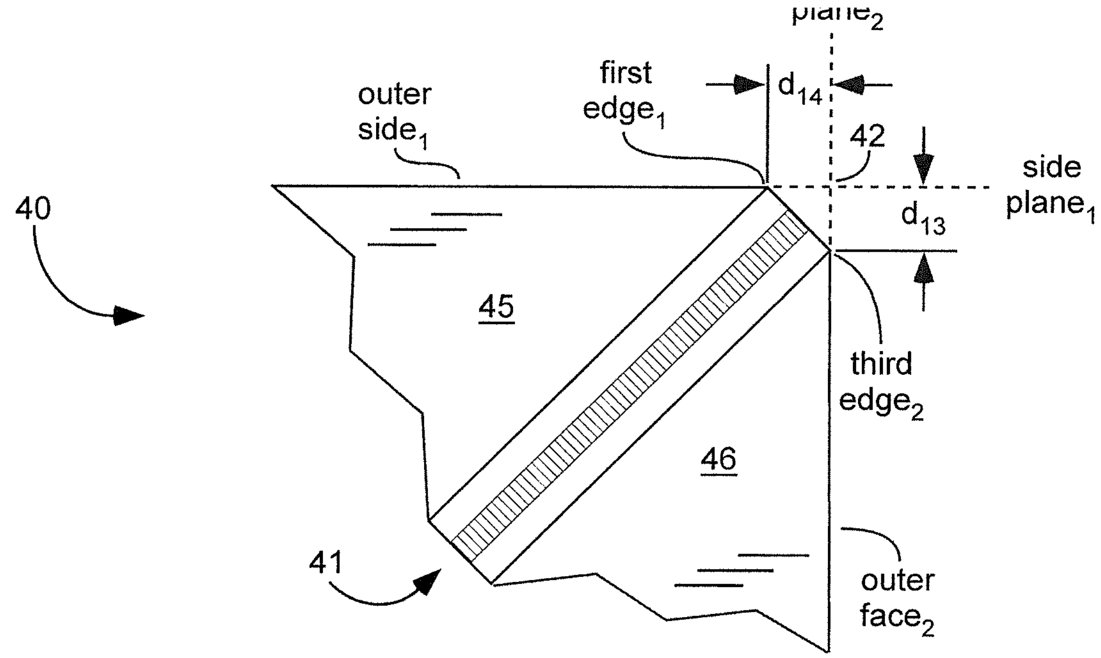
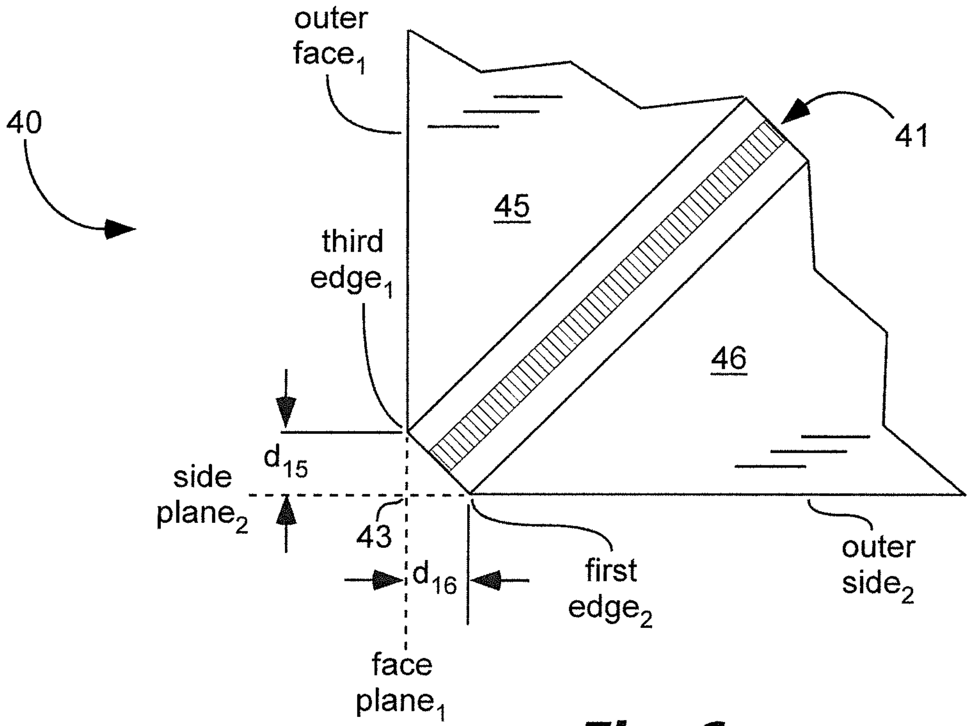

40
42
face
plane$_2$
first
edge$_1$
outer
side$_1$
side
plane$_1$
third
edge$_2$
first
prism
45
41
outer
face$_1$
outer
face$_2$
inner
face$_1$
second
prism
46
inner
face$_2$
third
edge$_1$
side
plane$_2$
first
edge$_2$
outer
side$_2$
face
plane$_1$
43

Fig. 4



plane2
first edge1
d14
outer side1
42
side plane1
d13
40
45
third edge2
46
41
outer face2

Fig. 5



outer face1
40
41
45
third edge1
46
d15
side plane2
43
d16
first edge2
outer side2
face plane1

Fig. 6

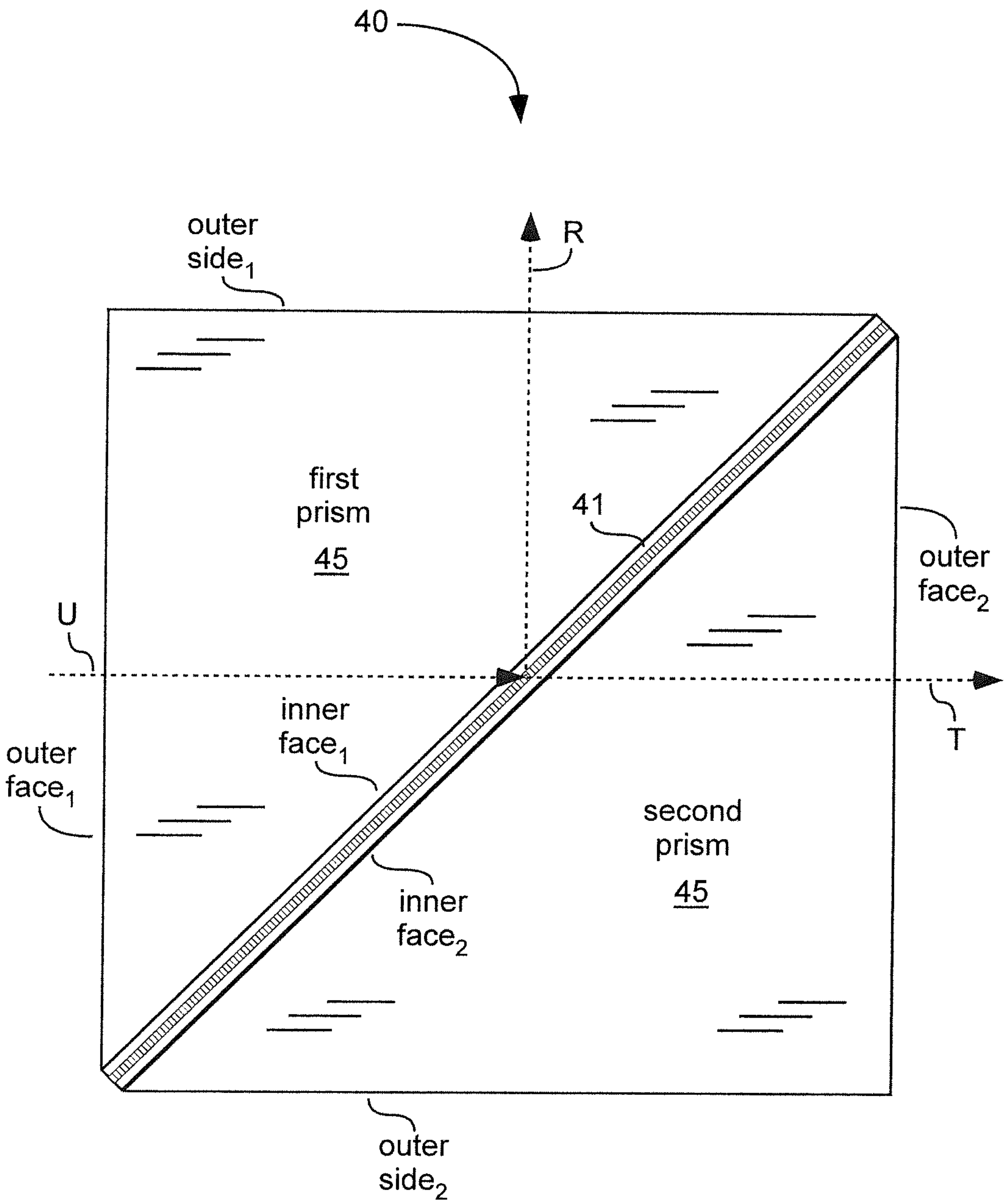

40
R
outer
side1
first
prism
45
41
outer
face2
U
inner
face1
outer
face1
T
second
prism
45
inner
face2
outer
side2

Fig. 7

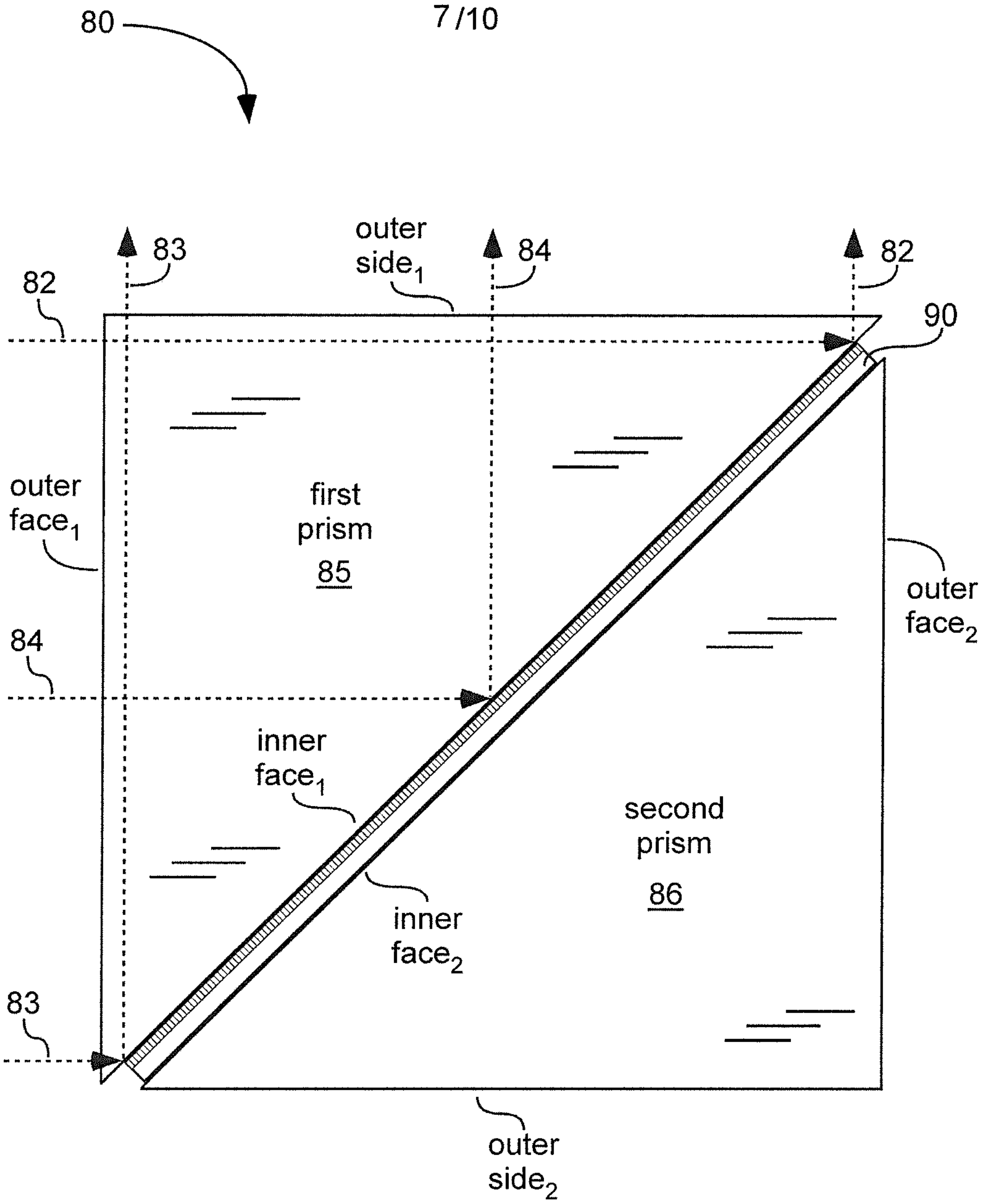

80
83
outer
side1
84
82
82
90
outer
face1
first
prism
85
outer
face2
84
inner
face1
second
prism
86
inner
face2
83
outer
side2

Fig. 8

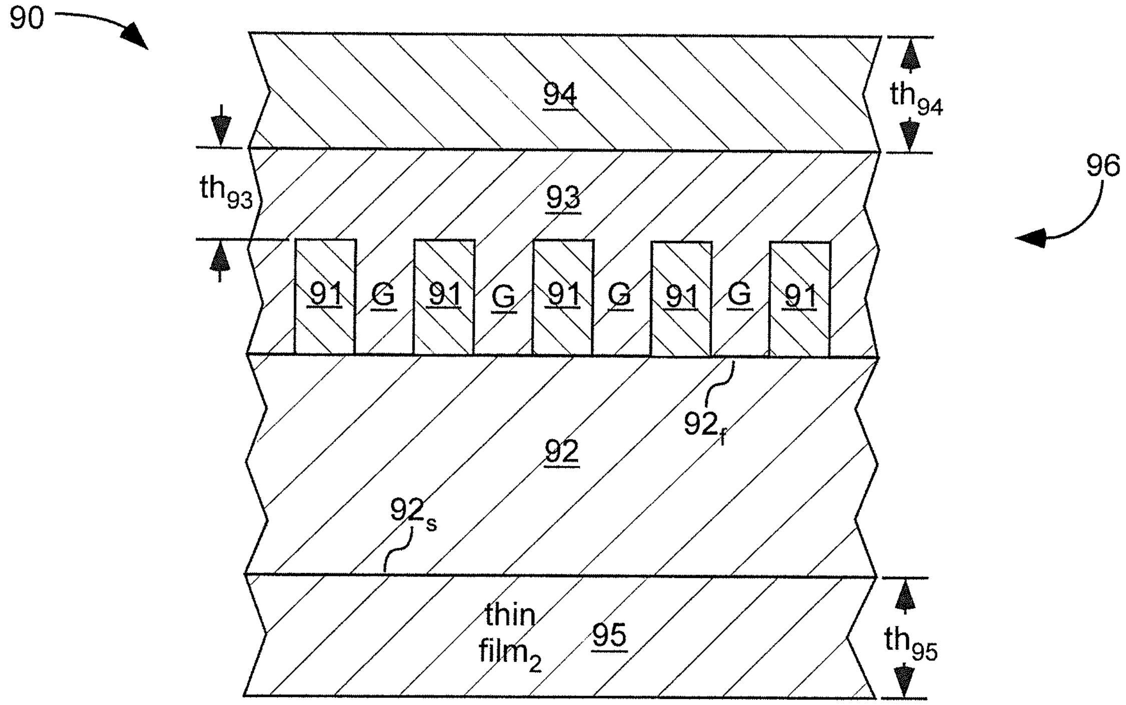

90
94
th$_{94}$
96
th$_{93}$
93
91
G
92$_f$
92
92$_s$
thin
film$_2$
95
th$_{95}$

Fig. 9

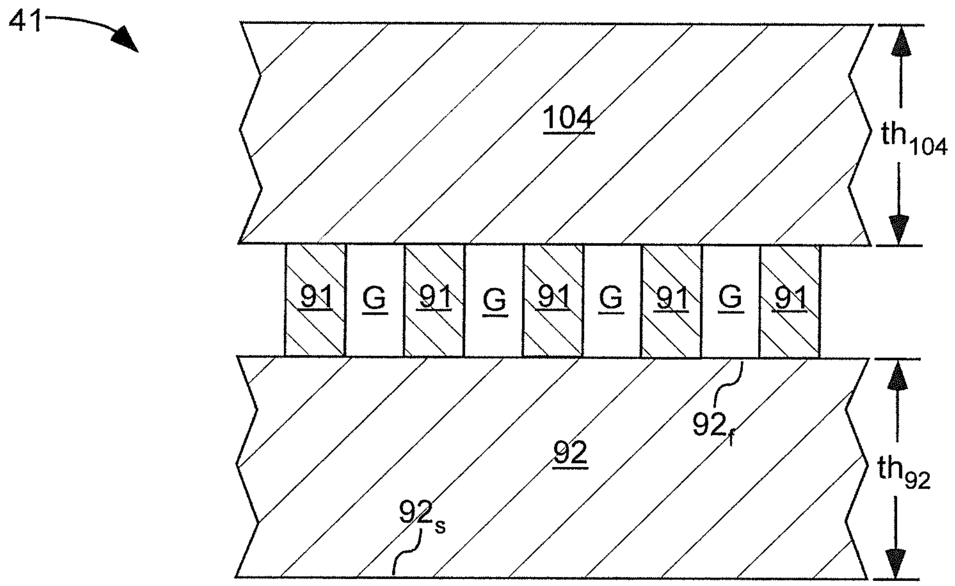

41
104
th$_{104}$
91
G
92$_f$
92
th$_{92}$
92$_s$

Fig. 10

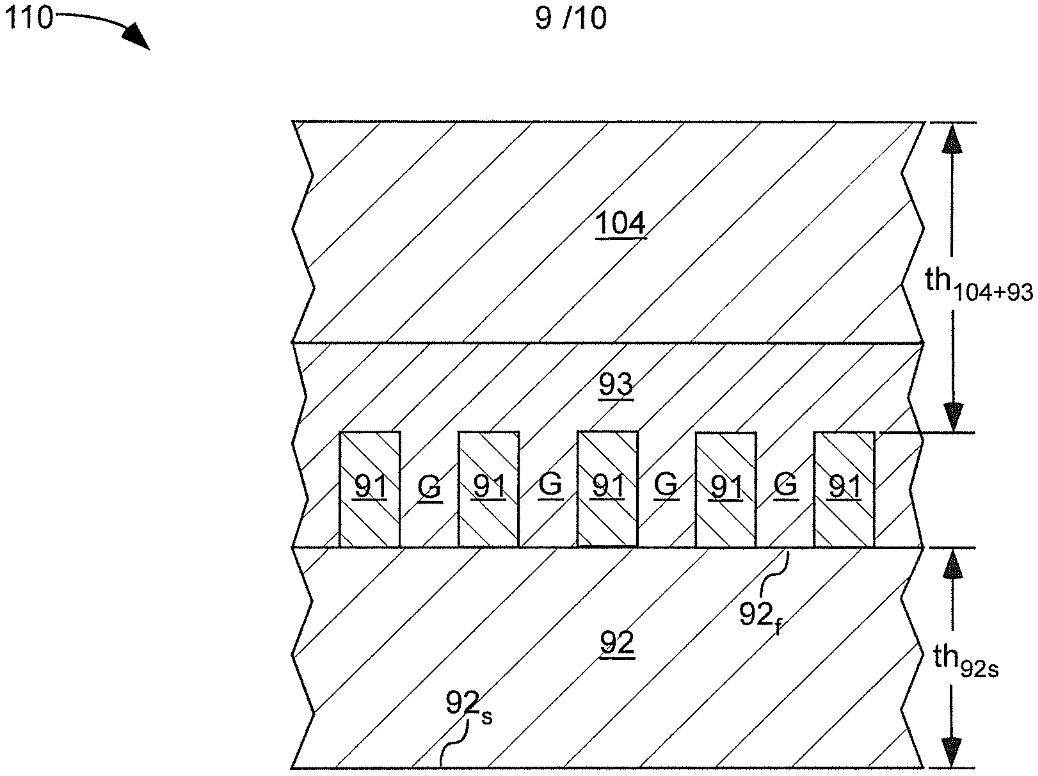

110
104
th104+93
93
91
G
92f
92
th92s
92s

Fig. 11

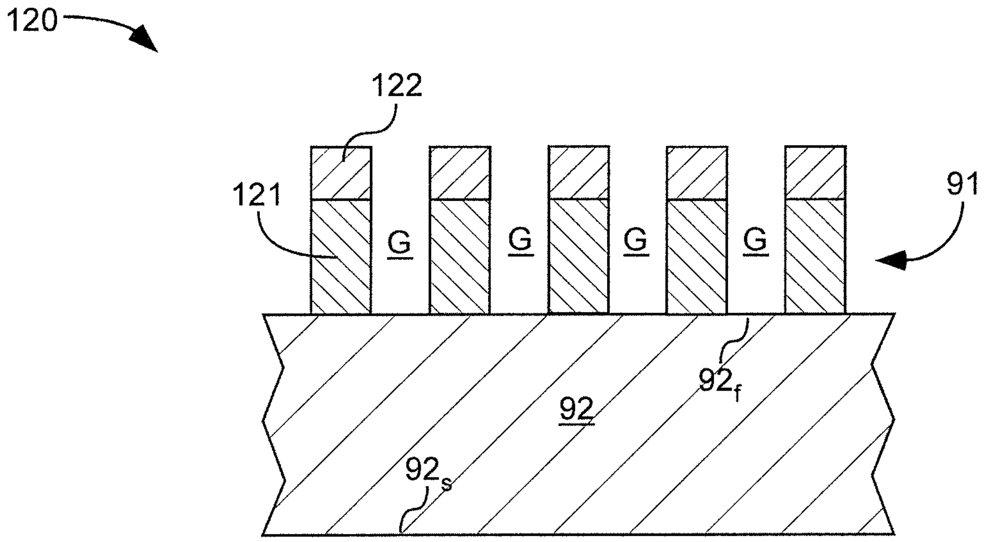

120
122
121
G
91
92f
92
92s

Fig.12

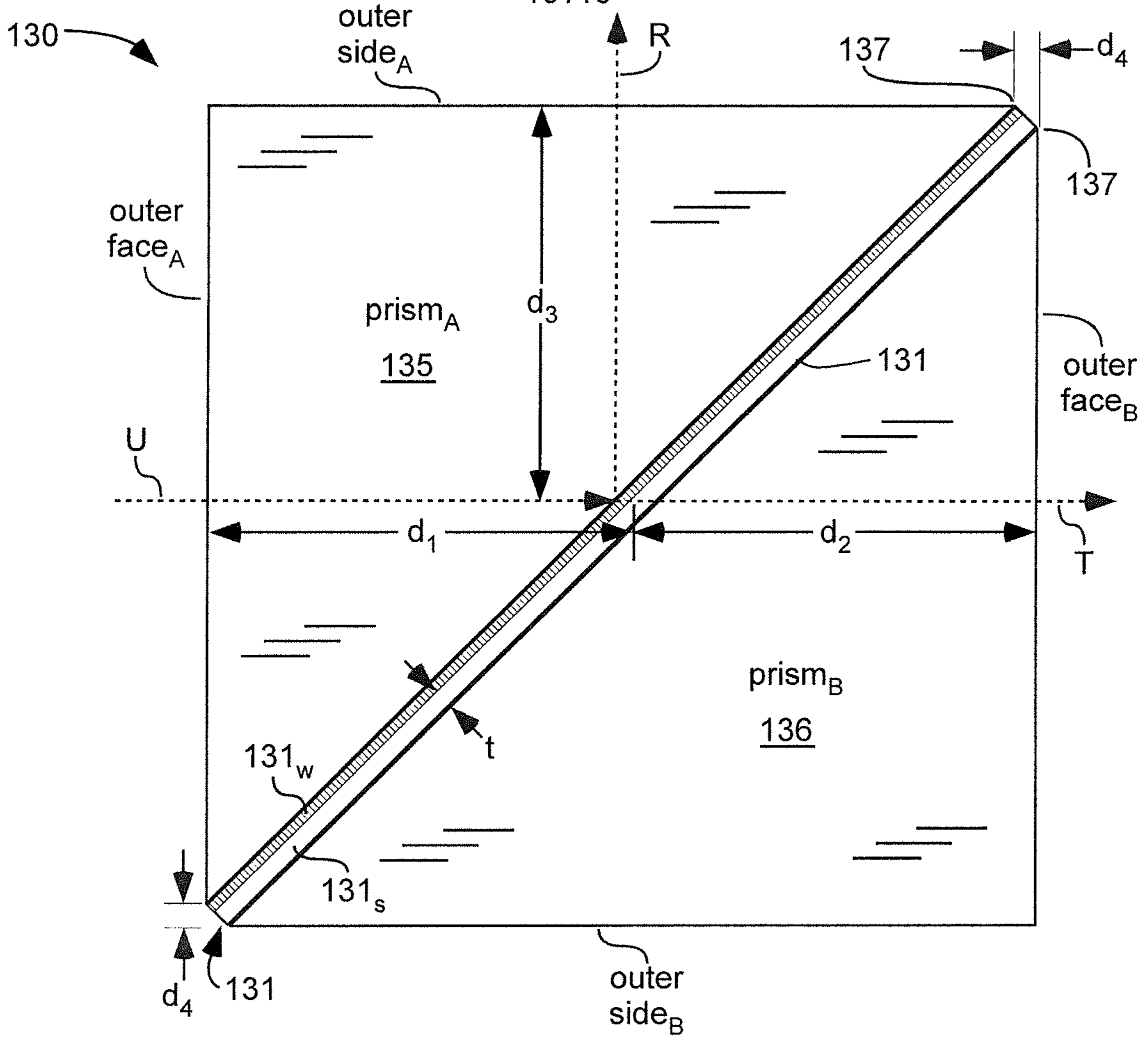


Fig. 13 prior art

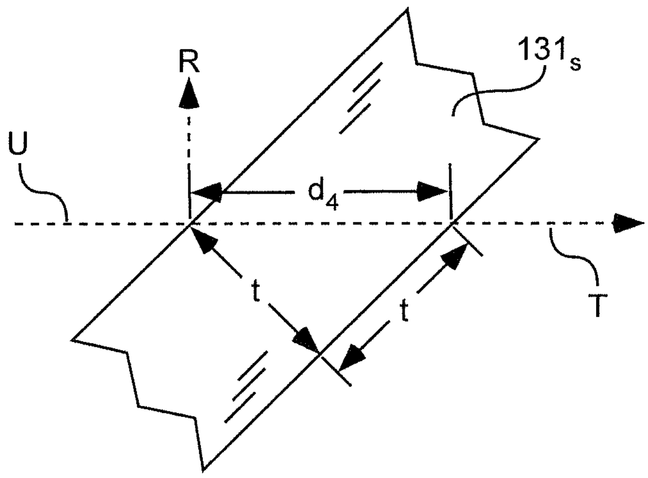


Fig. 14 prior art

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/028915

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G02B 5/30 (2015.01)
CPC - G02B 5/3058 (2015.04)
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(8) - G02B 5/00, 5/04, 5/30; G03B 21/00, 21/14 (2015.01)
USPC - 353/20; 359/201.1, 211.1, 211.3, 483.01, 487.03, 487.04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
CPC - G02B 5/00, 5/04, 5/18, 5/30.5/3025, 5/3058; G03B 21/00, 21/14 (2015.04) (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Orbit, Google Patents, Google, ProQuest
Search terms used: cube polarizer, prisms, wire grid polarizer, substrate, optical path length, silicon dioxide

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0297052 A1 (WANG et al) 27 December 2007 (27.12.2007) entire document	1-20
Y	US 6,212,014 B1 (LEHMAN, JR. et al) 03 April 2001 (03.04.2001) entire document	1-10
Y	US 2003/0076502 A1 (VERMA et al) 24 April 2003 (24.04.2003) entire document	3,4
Y	US 2006/0001837 A1 (HO) 05 January 2006 (05.01.2006) entire document	5,7,8
Y	US 2008/0278811 A1 (PERKINS et al) 13 November 2008 (13.11.2008) entire document	9,10,12,13,17-20
Y	US 2004/0120041 A1 (SILVERSTEIN et al) 24 June 2004 (24.06.2004) entire document	11-13
Y	US 2008/0286455 A1 (HAMAMOTO) 20 November 2008 (20.11.2008) entire document	14-20
Y	CREATH et al. Dynamic quantitative phase imaging for biological objects using a pixelated phase mask. Biomedical Optics Express. October 2012. pages 2866-2880. entire document	14-20

☐ 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
"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	Date of mailing of the international search report
05 August 2015	18 AUG 2015

Name and mailing address of the ISA/	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Blaine Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774