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(54) **Title:** ENCAPSULATED LIGHT-GUIDE OPTICAL ELEMENTS FOR NEAR EYE DISPLAY

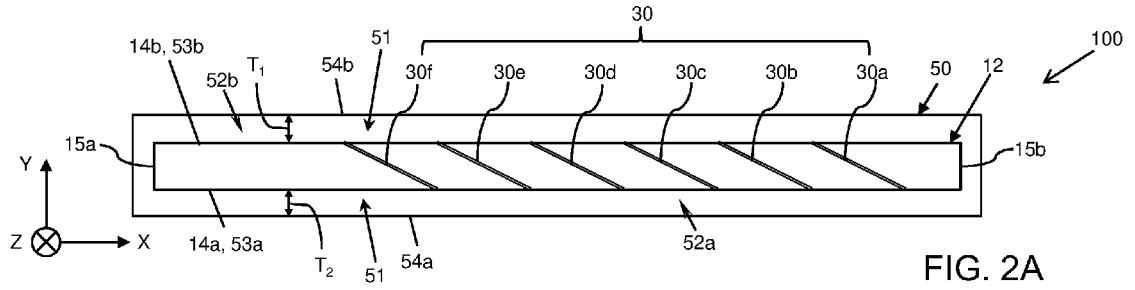


FIG. 2A

(57) **Abstract:** An optical device has an LOE formed from a light-transmitting material having a first refractive index. A pair of parallel major external surfaces of the LOE guide image illumination within the LOE by TIR. At least one optical coupling configuration of the LOE deflects a proportion of the image illumination that is guided within the LOE by TIR. An optical material includes at least one transparent material directly attached to the LOE at least at the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate the LOE. The optical material has a second refractive index less than the first refractive index to maintain conditions of TIR at the major external surfaces. In certain embodiments, the TIR-guided image illumination is incident to the major external surfaces at angles greater than a critical angle, including shallow angles.

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APPLICATION FOR PATENT

TITLE

Encapsulated Light-Guide Optical Elements for Near Eye Display

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from US Provisional Patent Application No. 63/210,672, filed June 15, 2021, US Provisional Patent Application No. 63/251,918, filed October 4, 2021, and US Provisional Patent Application No. 63/324,164, filed March 28, 2022, the disclosures of which are incorporated by reference in their entirety herein.

TECHNICAL FIELD

The present invention relates to optical devices, and in particular optical devices having an encapsulated light-guide optical element.

BACKGROUND OF THE INVENTION

Optical arrangements for near eye display (NED), head mounted display (HMD) and head up display (HUD) require large aperture to cover the area where the observer's eye is located (commonly referred to as the eye motion box – or EMB). In order to implement a compact device, the image that is to be projected into the observer's eye is generated by a small optical image generator (projector) having a small aperture that is multiplied to generate a large aperture. Aperture multiplication (expansion) can be achieved in various ways. One set of solutions for achieving aperture multiplication employ a light-guide optical element (LOE), and have been described in various publications by Lumus Ltd (Israel). In some example solutions, image illumination from the image projector is injected into the LOE so as to propagate through the LOE by total internal reflection at external surfaces of the LOE. The propagating illumination is progressively coupled out of the LOE towards an observer's eye either by use of obliquely angled partial reflectors or by use of a diffractive optical element on one surface of the LOE.

SUMMARY OF THE INVENTION

Embodiments of the present invention provide encapsulated light-guide optical elements (LOEs), optical devices having encapsulated LOEs, methods of fabricating optical devices having encapsulated LOEs, and methods of encapsulating LOEs. Each LOE of the disclosed embodiments is formed from a light-transmitting material, having a first refractive index, that supports propagation of image illumination by total internal reflection at a pair (and in certain embodiments two pairs) of planar parallel major external surfaces of the LOE, and includes at least one optical coupling configuration for redirecting / deflecting some of the propagating image illumination.

The LOE is at least partially encapsulated at the major external surfaces in a capsule formed from optical material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces of the LOE. The optical material (also referred to as low index material) is directly attached to the major external surfaces such that no intervening materials or substances (including air) are present between the low index material. As a result, the encapsulation is an air-gap free encapsulation. The low index material includes at least one transparent low index material. In certain embodiments, the low index material consists only of a single transparent low index material. In other embodiments, the low index material includes two adjacently placed transparent low index materials. In yet other embodiments, the low index material includes a transparent low index material and an adjacently placed light-absorbing low index material.

In certain preferred embodiments, the LOE is configured to perform one-dimensional aperture expansion, whereas in other preferred embodiments the LOE is configured to perform two-dimensional aperture expansion. In embodiments in which the LOE performs two-dimensional aperture expansion, a first region of the LOE performs a first stage of aperture expansion and a second region of the LOE performs a second stage of aperture expansion. In certain embodiments in which the LOE performs two-dimensional aperture expansion, a light-absorbing material is deployed at the portion of the low index material that is attached to the first region of the LOE. As mentioned, in certain embodiments, more than one low index material is used to encapsulate the LOE. Such embodiments are particularly useful in combination with embodiments in which the LOE performs two-dimensional aperture expansion whereby a first low index material is attached to a first region of the LOE that performs a first stage of aperture expansion, and a second low index material is attached to a second region of the LOE that performs a second stage of aperture expansion. In certain embodiments, both the first and second low index materials are transparent materials, and a light-absorbing material is deployed at the first low index material. In other embodiments, the second low index material is a transparent material and the first low index material is a light-absorbing material having inherently low refractive index.

According to the teachings of an embodiment of the present invention, there is provided optical device for directing image illumination towards a user for viewing. The optical device comprises: a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including a plurality of surfaces including a pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces, the LOE further including at least one optical coupling configuration for deflecting a proportion of the image illumination that is guided within the LOE by total internal

reflection at the major external surfaces; and an optical material including at least one transparent material directly attached to the LOE at least at the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate the LOE, the optical material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces, and the image illumination that is guided within the LOE by total internal reflection at the major external surfaces is incident to the major external surfaces at a range of angles greater than a critical angle defined by the first and second refractive indices, and the angles greater than the critical angle include shallow angles measured relative to the major external surfaces.

Optionally, the at least one transparent material is formed from a solid-state material.

Optionally, the at least one transparent material is formed from one or more layers of optical adhesive.

Optionally, the at least one transparent material is a thin coating layer of a polymer or dielectric material.

Optionally, the optical material has a thickness that is sufficiently small such that surface patterns of the optical material follow blemish patterns at the major external surfaces.

Optionally, the thickness is in a range from 2 μm to 20 μm.

Optionally, the first refractive index is in a range from 1.5 to 1.8.

Optionally, the second refractive index is in a range from 1.3 to 1.4.

Optionally, the at least one optical coupling configuration includes exactly one optical coupling configuration that deflects the proportion of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces out of the LOE towards the user.

Optionally, the optical coupling configuration is implemented as a plurality of mutually parallel partially reflecting surfaces deployed within the LOE and oblique to the major external surfaces.

Optionally, the optical coupling configuration is implemented as at least one diffractive element associated with one of the major external surfaces.

Optionally, the LOE includes a first region and a second region, and the at least one optical coupling configuration includes a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration

configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region.

Optionally, the first optical coupling configuration is implemented as a first plurality of mutually parallel partially reflecting surfaces having a first orientation, and the second optical coupling configuration is implemented as a second plurality of mutually parallel partially reflecting surfaces having a second orientation that is non-parallel to the first orientation.

Optionally, the first optical coupling configuration is implemented as a first at least one diffractive element associated with one of the major external surfaces, and the second optical coupling configuration is implemented as a second at least one diffractive element associated with one of the major external surfaces.

Optionally, the optical device further comprises: a light-absorbing material deployed in association with one or more portions of the at least one transparent material in the first region.

Optionally, the light-absorbing material has a refractive index that is equal to the first refractive index or no more than 10% greater than the first refractive index.

Optionally, the optical device further comprises: at least one optical element attached to the at least one transparent material.

Optionally, the at least one optical element includes: a lens attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

Optionally, the at least one optical element includes: a first lens attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a second lens attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

Optionally, the at least one optical element includes: a first protective film attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a second protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

Optionally, the LOE is a pre-cut LOE that is cut from a precursor LOE prior to the optical material being directly attached to the LOE such that the LOE includes substantially only an active area in which the image illumination propagates, and one or more perimeter edges of the LOE are coated with at least one layer of opaque material.

There is also provided according to an embodiment of the teachings of the present invention a method for fabricating an optical device that directs image illumination towards a user

for viewing. The method comprises: obtaining a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including a plurality of surfaces including a pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces, the LOE further including at least one optical coupling configuration for deflecting a proportion of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces, and the image illumination that is guided within the LOE by total internal reflection at the major external surfaces is incident to the major external surfaces at a range of angles greater than a critical angle defined by the first and second refractive indices, and the angles greater than the critical angle include shallow angles measured relative to the major external surfaces; and directly attaching an optical material that includes at least one transparent material to the LOE at least at the major external surfaces such that the optical material directly contacts the major external surfaces and at least partially encapsulates the LOE, the optical material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces.

Optionally, the LOE includes an active area in which the image illumination propagates and an inactive area in which the image illumination does not propagate or in which the image illumination is not directed towards the user, and the method further comprises: prior to directly attaching the optical material to the LOE: modifying the LOE to remove the inactive area such that substantially only the active area of the LOE remains, thereby producing a modified LOE, and coating one or more perimeter edges of the modified LOE with at least one layer of opaque material

Optionally, the optical material is additionally directly attached to the opaque material at the one or more perimeter edges of the modified LOE.

Optionally, the method further comprises: cutting or trimming the optical material to achieve a contour of an eyepiece.

Optionally, the method further comprises: attaching at least one optical element to the at least one transparent material.

Optionally, the at least one optical element includes: a lens attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

Optionally, the at least one optical element includes: a first lens attached to a first portion of the at least one transparent material that is directly attached to a first of the major external

surfaces, and a second lens attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

Optionally, the at least one optical element includes: a first protective film attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a second protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

Optionally, the LOE includes a first region and a second region, and the at least one optical coupling configuration includes a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region, and the method further comprises: deploying a light-absorbing material in association with one or more portions of the at least one transparent material in the first region.

Optionally, the light-absorbing material has a refractive index that is equal to the first refractive index or no more than 10% greater than the first refractive index.

Optionally, directly attaching the at least one transparent material to the LOE includes performing a process selected from the group consisting of: dip-coating, spin coating, bonding, and molding.

There is also provided according to an embodiment of the teachings of the present invention an optical device for directing image illumination towards a user for viewing. The optical device comprises: a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including: a plurality of surfaces including at least one pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces, a first region and a second region, and a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region; a transparent material directly attached to the LOE at least at

the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate the LOE, the transparent material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces; and a light-absorbing material deployed in association with one or more portions of the transparent material in the first region.

There is also provided according to an embodiment of the teachings of the present invention an optical device for directing image illumination towards a user for viewing. The optical device comprises: a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including: a plurality of surfaces including at least one pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces, a first region and a second region, and a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region; a light-absorbing material directly attached to the LOE at the major external surfaces in the first region so as to be in direct contact with the major external surfaces in the first region; and a transparent material directly attached to the LOE at the major external surfaces in the second region so as to be in direct contact with the major external surfaces in the second region, the transparent material and the light-absorbing material cooperating to at least partially encapsulate the LOE, and each of the transparent material and the light-absorbing material having a refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces.

There is also provided according to an embodiment of the teachings of the present invention an optical device for directing image illumination towards a user for viewing. The optical device comprises: a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including: a plurality of surfaces including at least one pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces, a first region and a second region, and a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the

major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region; at least one transparent material directly attached to the LOE at least at the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate the LOE, the at least one transparent material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces; at least one protective film associated at least with a portion of the at least one transparent material such that the at least one protective film is associated with a portion of at least one of the major external surfaces in the first region; and a coating deployed on at least a portion of the at least one protective film such that the coating is associated with the portion of the at least one transparent material.

Optionally, in any one of the optical devices according to embodiments of the present invention the first region is configured as a first LOE section having two pairs of parallel major external surfaces forming a rectangular cross-section such that the image illumination propagates through the first LOE section by total internal reflection at the two pairs of parallel major external surfaces.

Within the context of this document, the term "guided" generally refers to light that is trapped within a light-transmitting material (e.g., a substrate) by total internal reflection at major external surfaces of the light-transmitting material such that the light that is trapped within the light-transmitting material propagates in a propagation direction through the light-transmitting material.

Unless otherwise defined herein, 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 may 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 addition, the materials, methods, and examples are illustrative only and are not intended to be necessarily limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

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 is a schematic side view of an optical device having a light-guide optical element (LOE), having a pair of parallel faces and partially-reflecting surfaces oblique to the parallel faces, that can be used with embodiments of the present invention;

FIGS. 2A – 2C are schematic side, plan, and front views, respectively, of an optical device having an LOE similar to the LOE of FIG. 1, encapsulated by a capsule formed from a transparent material having a refractive index lower than the refractive index of the LOE, according to embodiments of the present invention;

FIG. 3 is a schematic front view similar to FIG. 2C, but showing active and inactive areas of the LOE;

FIG. 4A is a schematic front view of an LOE that has been trimmed or cut to remove the inactive area, according to embodiments of the present invention;

FIG. 4B is a schematic front view of the LOE of FIG. 4A, showing perimeter edges of the LOE onto which a coating of opaque material has been applied, according to embodiments of the present invention;

FIGS. 4C and 4D are schematic front and plan views, respectively, of the LOE of FIG. 4B encapsulated by a capsule formed from a transparent material having a refractive index lower than the refractive index of the LOE, according to embodiments of the present invention;

FIG. 4E is a schematic front view of the encapsulated LOE of FIGS. 4C and 4D, showing the capsule after having been trimmed or cut to have an eyepiece contour, according to embodiments of the present invention;

FIG. 4F is a schematic front view of an encapsulated LOE similar to FIG. 4E, but showing the encapsulated LOE after being modified to include a coupling-in region that can accommodate an optical coupling-in configuration, according to embodiments of the present invention;

FIGS. 5A and 5B are schematic side and plan views, respectively, of an encapsulated LOE having a lens and a protective film respectively attached to first and second surfaces of the capsule, according to embodiments of the invention;

FIGS. 6A and 6B are schematic side and plan views, respectively, of an encapsulated LOE having first and second protective films respectively attached to first and second surfaces of the capsule, according to embodiments of the invention;

FIGS. 7A and 7B are schematic side and plan views, respectively, of an encapsulated LOE having first and second lenses respectively attached to first and second surfaces of the capsule, according to embodiments of the invention;

FIGS. 8A and 8B are schematic side and plan views, respectively, of an encapsulated LOE having first and second lenses, each having a protective coating or film applied thereto, respectively attached to first and second surfaces of the capsule, according to embodiments of the invention;

FIGS. 9A and 9B are schematic front and side views, respectively, of an optical device having an LOE configured for performing two-dimensional aperture expansion encapsulated by a capsule formed from a transparent material having a refractive index lower than the refractive index of the LOE, according to embodiments of the present invention;

FIG. 10 is a schematic front view of the encapsulated LOE of FIGS. 9A and 9B, showing the capsule after having been trimmed or cut to have an eyepiece contour, according to embodiments of the present invention;

FIG. 11 is a schematic side view of an encapsulated LOE similar to FIG. 9B, showing a lens and a protective film respectively attached to first and second surfaces of the capsule, according to embodiments of the invention;

FIG. 12 is a schematic partial side view of the LOE of FIGS. 9A and 9B, showing escaped light from the LOE reflected back into the LOE by an external surface of the capsule, and also showing light from an external scene reflected toward a user by an optical coupling configuration associated with the LOE;

FIGS. 13A and 13B are schematic front and side views similar to FIGS. 9A and 9B, showing a light-absorbing material associated with portions of the transparent material that form the capsule, according to embodiments of the present invention;

FIG. 14 is a schematic partial side view of the LOE of FIGS. 13A and 13B, showing the light-absorbing material absorbing escaped light from the LOE and light from an external scene, according to embodiments of the present invention;

FIG. 15 is a schematic side view showing an encapsulated LOE similar to as shown in FIG, 9B, but in which the capsule is formed from two transparent materials each having a refractive index lower than the refractive index of the LOE, according to embodiments of the present invention;

FIGS. 16A and 16B are schematic side and plan views, respectively, of an encapsulated LOE similar to the LOE shown in FIG. 15, but also showing a protective film on the transparent

materials on one side of the LOE and an additional coating layer on a portion of the protective film, according to embodiments of the present invention;

FIGS. 17A and 17B are schematic side and front views, respectively, of an optical device having an LOE configured for performing two-dimensional aperture expansion encapsulated by a capsule formed from first and second transparent materials each having a refractive index lower than the refractive index of the LOE, according to another embodiment of the present invention;

FIG. 18 is a schematic side view of the optical device of FIGS. 17A and 17B, additionally showing a lens and a protective film respectively attached to portions of the first and second surfaces of the capsule, according to embodiments of the invention; and

FIG. 19 is a schematic side view of the optical device of FIGS. 17A and 17B, additionally showing a light-absorbing material associated with portions of the first transparent material of the capsule, according to embodiments of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the present invention provide encapsulated light-guide optical elements (LOEs), optical devices having encapsulated LOEs, methods of fabricating optical devices having encapsulated LOEs, and methods of encapsulating LOEs. The encapsulated LOEs according to the embodiments of the present invention are particularly suitable for use as part of a near eye display or head up display for augmented reality applications.

The principles and operation of the LOEs, optical devices and methods according to embodiments of the present invention may be better understood with reference to the drawings accompanying the description.

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. Initially, throughout this document, references are made to directions, such as, for example, front and back, and the like. These directional references are exemplary only, and are used only for ease of presentation and refer to the arbitrary orientations as illustrated in the drawings. The LOEs and optical devices may be deployed in any required orientation.

By way of introduction, FIG. 1 schematically illustrates a light-guide optical element (LOE) **12** that can be used with embodiments of the present invention. Initially, it is noted that the LOE **12** in FIG. 1 is part of an optical device **10** that can include other optical components besides the LOE **12**, most notably an image projector **18** and an optical coupling-in configuration **22**. Such

components may also be present in optical devices constructed and operative according to embodiments of the present invention.

The LOE **12** is formed as a parallel-faced slab (also referred to as a substrate) of transparent (i.e., light-transmitting) material within which image illumination propagates (i.e., is guided) by total internal reflection at external surfaces of the slab. In this particular embodiment, the LOE **12** has a plurality of surfaces including a pair of planar parallel major external surfaces (faces) **14**a, **14**b for guiding the image illumination (light) by total internal reflection.

The image projector **18** generates an image **20**, as represented here schematically by a beam of illumination **20** including sample rays **20**A and **20**B which span the beam. The image **20** is coupled into the LOE **12** by the optical coupling-in configuration **22**, as illustrated here schematically by a coupling prism **22** (although any suitable coupling-in arrangement, including coupling reflectors and diffractive gratings, can be used), so as to generate reflected rays **24** which are trapped by total internal reflection within the LOE **12**, generating also rays **26**. Here, the coupling prism **22** includes three major surfaces, one of which is located next to (or is common with) a slant edge **28** of the LOE **12** (where the edge **28** is at an oblique angle to the major external surfaces **14**a, **14**b).

The coupled-in image **20** propagates along the LOE **12** by repeated total internal reflection from the major external surfaces **14**a, **14**b, impinging on an optical coupling-out configuration **30**, as illustrated here schematically by a sequence of mutually parallel partially reflecting internal surfaces **30**a, **30**b, **30**c, **30**d, **30**e, **30**f (collectively designated **30**) at an oblique angle (α_{sur}) to the major external surfaces **14**a, **14**b, where part of the image intensity is reflected so as to be deflected (coupled out) of the substrate as rays **32A** and **32B** toward the pupil **34** of an eye **36** (of an observer / user) that is located in eye motion box (EMB) **38** at a an eye relief (ER) distance **40** from the major external surface **14**a. The transparency of the LOE **12** enables the observer to view the coupled-out image **20** overlaid on the view of the external scene (i.e., real-world scene) at the front side of the LOE **12** (i.e., at the face **14**b), which is of particular use when the optical device **10** is deployed as part of an augmented reality (AR) system.

In order to minimize unwanted reflections of the image **20** which might give rise to ghost images, the partially reflecting internal surfaces (also referred to herein as "facets") **30** are preferably coated with reflective coating so as to have low reflectance for a first range of incident angles, while having the desired partial reflectivity for a second range of incident angles, where a ray with a small inclination to the normal to a partially reflecting surface **30** (represented here as angle β_{ref}) is split in order to generate a reflected ray for coupling out, while a high inclination (to the normal) ray is transmitted with negligible reflection.

The image **20** is a collimated image, i.e., where each pixel is represented by a beam of parallel rays at a corresponding angle, equivalent to light from a scene far from the observer (the collimated image is referred to as being "collimated to infinity"). The image is represented here simplistically by rays corresponding to a single point in the image, typically a centroid of the image, but in fact includes a range of angles to each side of this central beam, which are coupled into the substrate with a corresponding range of angles, and similarly coupled out at corresponding angles, thereby creating a field of view (FOV) corresponding to parts of the image arriving in different directions to the eye **36** of the observer.

Although the image projector **18** is schematically illustrated here as a rectangle, the image projector **18** includes at least one light source, typically deployed to illuminate a spatial light modulator, such as an LCOS chip. The spatial light modulator modulates the projected intensity of each pixel of the image, thereby generating an image. Alternatively, the image projector may include a scanning arrangement, typically implemented using a fast-scanning mirror, which scans illumination from a laser light source across an image plane of the projector while the intensity of the beam is varied synchronously with the scanning motion on a pixel-by-pixel basis, thereby projecting a desired intensity for each pixel. In both cases, collimating optics are provided to generate an output projected image which is collimated to infinity. Some or all of the above components are typically arranged on surfaces of one or more polarizing beam splitter (PBS) cube or other prism arrangement, as is well known in the art

The performance of the LOE **12** is strongly dependent on the total internal reflection (TIR) of the image illumination across the entire desired field. As is known in the art, the principles of TIR are governed by critical angle, which is determined by the refractive index of the material from which the LOE **12** is constructed (typically glass, for example BK7 which has a refractive index of approximately 1.52) and the refractive index of the surrounding medium contacting the LOE **12**. Specifically, the critical angle for light propagation through he LOE is defined as $\theta_c = \sin^{-1}\frac{\eta_m}{\eta_L}$, where η_m is the refractive index of the medium surrounding the LOE, and η_L is the refractive index of the LOE. For example, if the LOE is constructed from BK7 and the medium immediately contacting the major external surfaces **14**a, **14**b is air (which has a refractive index that is practically unity, i.e., a refractive index of 1), then $\theta_c = \sin^{-1}\frac{1}{1.52} \approx 41.1°$.

Thus, the performance of the LOE **12** is generally determined by the angles of the propagating light field within the LOE **12**, and the refractive indices of the LOE **12** and the surrounding medium.

In conventional optical devices that utilize LOEs to perform aperture multiplication (i.e., aperture expansion), such as the optical device **10** of FIG. 1, the surrounding medium that contacts the major surfaces **14**a, **14**b of the LOE is typically air. This can present problems in several respects. In one respect, directly contacting the major surfaces **14**a, **14**b of the LOE with air can leave the LOE exposed to the environment thus leaving the LOE unprotected from damage and reducing the overall mechanical stability of the optical device. This also reduces the mechanical contact area of the LOE to other functional or mechanical elements, such a mechanical body that supports the LOE, in particular eyeglass frames in which the LOE can be mounted in certain near-eye display implementations. In another respect, deployment of additional optical elements, such as lenses or optical films, to the major external surfaces **14**a, **14**b while maintaining a small form factor and good optical performance can be particularly difficult. For example, direct bonding of additional optical elements to the major LOE surfaces can negatively impact TIR due to the refractive index of the bonding material (e.g., optical cement), which is less than the refractive index of the LOE but is typically higher than that of air and therefore increases critical angle thereby reducing the effective FOV. Conditions of TIR with lower critical angle can be maintained with an air gap between the additional optical element and the LOE **12**, however such air gaps increase the thickness of the optical device resulting in a bulkier device, and also reduce the mechanical stability of the device.

In order to overcome these limitations, embodiments of the present invention provide an LOE that is formed from a material having a moderate to moderately high refractive index, and that is at least partially encapsulated in an encapsulation structure formed from optical material, that includes at least one transparent material, having a lower refractive index than the LOE but still greater than unity.

Turning now to FIGS. 2A – 2C, there is schematically illustrated an optical device, generally designated **100**, constructed and operative according to an embodiment of the present invention. Here, the optical device **100** includes LOE **12**, and also includes an encapsulation structure **50** that is formed from optical material **51** that encapsulates the LOE **12**. The optical device **100** can be shaped to approximately form of an eyepiece, that is an eyepiece that is part of a near-eye display, for example as part of an eyeglasses form factor. It is noted that the LOE illustrated in FIGS. 2A – 2C is similar in structure to the LOE illustration FIG. 1 with the notable exceptions that the LOE illustrated in FIGS. 2A – 2C is not shown with a slant edge, and no optical coupling-in configuration is shown in FIGS. 2A – 2C. This is for clarity of presentation only, as encapsulated LOEs according to embodiments of the present disclosure may include one or more slant edges (i.e., edges or surfaces that are oblique to the parallel surfaces **14**a, **14**b), and optical

coupling-in configurations used with encapsulated LOEs will be discussed in subsequent sections of the present disclosure.

Also illustrated in FIGS. 2A – 2C are two additional sets of external surfaces **15**a, **15**b and **16**a, **16**b of the LOE **12**. These surfaces **15**a, **15**b, **16**a, **16**b are also referred to as perimeter surfaces / edges or peripheral surfaces / edges **15**a, **15**b, **16**a, **16**b. Each of the pairs of surfaces **15**a, **15**b and **16**a, **16**b can, in certain embodiments, be a pair of parallel surfaces. In certain embodiments, both pairs of surfaces **14**a, **14**b and **15**a, **15**b is a pair of parallel surfaces and the three pairs of surfaces **14**a, **14**b, **15**a, **15**b, **16**a, **16**b are mutually perpendicular.

The encapsulation structure **50** (also referred to herein interchangeably as a "capsule") and the LOE **12** are arranged such that the optical material **51** of the capsule **50** is directly attached to the LOE **12** at least at the major external surfaces **14**a, **14**b so as to be in direct contact (i.e., at a direct abutment) with the major external surfaces **14**a, **14**b, thereby encapsulating the LOE **12**. By direct contact, it is meant that no intermediate layer(s) of material(s) is/are present between the optical material **51** of the capsule **50** and the major external surfaces **14**a, **14**b of the LOE **12**. Such intermediate materials include solid materials, semi-solid materials, as well as air. Therefore, it should be made clear that a key distinction of the encapsulated LOEs according to embodiments of the present invention is that no air gap is present between the optical material **51** of the capsule **50** and the major external surfaces **14**a, **14**b of the LOE **12**.

In certain embodiments of the present invention, the LOE **12** is formed from a light-transmitting material having a moderate to moderately high refractive index, preferably a refractive index that falls in a range from 1.5 to 1.8 (i.e., $1.5 \leq \eta_L \leq 1.8$). The encapsulation structure **50** is formed from an optical material **51** having a refractive index that is less than the refractive index of the LOE but is still greater than the refractive index of air (i.e., greater than unity). In preferred embodiments, the encapsulation structure **50** is formed from an optical material **51** having a refractive index that falls in a range from 1.1 to 1.4 (i.e., $1.1 \leq \eta_m \leq 1.4$), more preferably in a range from 1.2 to 1.4 (i.e., $1.2 \leq \eta_m \leq 1.4$), and most preferably in a range from 1.3 to 1.4 (i.e., $1.3 \leq \eta_m \leq 1.4$). In one non-limiting embodiment, the encapsulation structure **50** is formed from a transparent material in the form of an optical adhesive having a refractive index of approximately 1.34 (i.e., $\eta_L = 1.34$), for example an optical adhesive available from Norland Products, Inc. of Jamesburg, NJ, USA. A detailed discussion of the types of transparent materials from which the capsule **50** can be formed is provided in subsequent sections of the present disclosure.

The optical material from which the encapsulation structure **50** is formed is referred to interchangeably herein as a low index material **51**. Within the context of the present document, the

term "low" in the expression "low index" is taken relative to the refractive index of the LOE **12**. In other words, the optical material **51** has a low refractive index in comparison to the refractive index of the LOE **12**, i.e., the optical material has a lower refractive index than the refractive index of the LOE **12** (preferably the optical material has a refractive index that is at least approximately 7% lower than the refractive index of the LOE).

In the disclosed embodiments, the optical material **51** includes at least one transparent material. As will be discussed, in certain embodiments, a single transparent material is used to encapsulate the LOE. In other embodiments, two transparent materials (arranged adjacent to each other) are used to encapsulate the LOE. In yet other embodiments, a transparent material and a light-absorbing material are used to encapsulate the LOE. All such transparent materials and light-absorbing materials used for encapsulation according to the embodiments of the present invention are low index materials in accordance with the definition of low index material defined above.

By constructing the LOE **12** from a moderate to moderately high refractive index material and providing a capsule **50** formed from a low index material **51**, conditions of TIR can be maintained with a usable critical angle when the LOE **12** is encapsulated in the capsule **50**. For example, using the extreme values of the refractive index ranges above as a basis, a critical angle in a range from approximately 37.7° (when $\eta_m = 1.1$ and $\eta_L = 1.8$) to 69° (when $\eta_m = 1.4$ and $\eta_L = 1.5$) can be achieved.

In certain embodiments, it may be desirable to inject image illumination into the LOE **12** such that the injected illumination propagates by TIR and is incident to the major surfaces **14**a, **14**b at a range of angles that are greater than the critical angle, including shallow angles which are measured relative to the planes of the major external surfaces **14**a, **14**b. These shallow angles correspond to high angle of incidence (AOI), preferably AOIs in a range between 60° to 80°. The propagation of image illumination within the LOE by TIR at angles greater than the critical angle that include shallow angles has an advantageous effect of including a larger portion of the light field of the image. This may be of particular value in situations in which the critical angle is larger than a preferred angle (e.g., larger than 50°) which results in a larger portion of the light field being below the critical angle and thus not being trapped in the LOE **12**. Injecting the image illumination into the LOE such that the image illumination is trapped within the LOE by TIR at the major surface **14**a, **14**b and such that the propagating image illumination is incident to the major surfaces **14**a, **14**b at a range of angles that are greater than the critical angle that include shallow angles can be accomplished by appropriately designing the optical coupling-in configuration, for example by appropriately designing the angle of a coupling-in prism or coupling-in reflector.

It is noted that in FIGS. 2A – 2C, the LOE **12** is shown as being encapsulated by the capsule **50** such that in addition to being in direct contact with the of the surfaces **14**a, **14**b, the low index material **51** is also in direct contact with the entirety of the surfaces **15**a, **15**b (as seen in FIGS. 2A and 2C) as well as the entirety of the surfaces **16**a, **16**b (as seen in FIGS. 2B and 2C). Despite FIGS. 2A – 2C showing direct contact of the low index material with the surfaces **15**a, **15**b, **16**a, **16**b, this contact is only optional, and encapsulation at the major external surfaces **14**a, **14**b is the preferred minimum amount of encapsulation as this encapsulation provides the necessary working conditions for TIR. In fact, in certain non-limiting implementations it may be more practical to encapsulate the LOE such that the low index material is only attached at the major surfaces of the LOE.

In certain preferred embodiments, the encapsulation at the major external surfaces **14**a, **14**b is a full encapsulation whereby a layer of the low index material **51** extends across the entirety of the length of each the major external surfaces **14**a, **14**b. However, in other preferred embodiments the low index material may (in certain cases) partially extend across the length of the major external surfaces **14**a, **14**b thereby possibly leaving end portions (just before the surfaces **15**a, **15**b) of the LOE **12** uncontacted by the low index material. Preferably, the partial extension covers the portions of the major external surfaces **14**a, **14**b through which the image illumination propagates and ultimately reaches the eye of the observer. Preferably, this partial extension is across the vast majority (or bulk) of the length of the major external surfaces **14**a, **14**b (where vast majority of the length refers to preferably at least 80% of the length, and more preferably at least 90% of the length, and even more preferably at least 95% of the length). In these "partial extension" embodiments, the LOE is considered to be "partially encapsulated".

In the arbitrarily labeled xyz coordinate system used in the drawings, the "length" is measured along the x-dimension. It is also noted that the low index material **51** preferably extends across the entirety of the major external surfaces **14**a, **14**b in the transverse direction (perpendicular to the length), which in the arbitrarily labeled xyz coordinate system used in the drawings is measured along the z-dimension. In other words, the low index material preferably extends just up to the edges **16**a, **16**b.

As stated above, in certain non-limiting embodiments the low index material extends just up to the edges **15**a, **15**b in the length dimension (x-dimension in the drawings). However, in certain cases the low index material may extend beyond the edges **15**a, **15**b in the length dimension (x-dimension in the drawings) such that portions of the low index material are in direct contact with the edges **15**a, **15**b. In certain cases the low index material may also extend beyond the edges

16a, **16**b in the transverse dimension (z-dimension in the drawings) such that portions of the low index material are in direct contact with the edges **16**a, **16**b.

The layer (or layers) of the low index material **51** of the capsule **50** that extends across the length of the surface **14**a corresponds to a first region **52**a of the capsule **50** that is directly attached to the surface **14**a. Similarly, the layer (or layers) of the low index material **51** of the capsule **50** that extends across the length of the surface **14**b corresponds to a second region **52**b of the capsule **50** that is directly attached to the surface **14**b. The low index material **51** has interior/internal contact portions that directly contact the LOE at the major external surfaces **14**a, **14**b. These interior/internal contact portions are also referred to as "interfacing" portions. A first of the contact portions **53**a is in the first region **52**a of the low index material **51**, and directly contacts the LOE **12** at the surface **14**a so as to form an interface between the low index material **51** and the surface **14**a of the LOE **12**. Similarly, a second of the contact portions **53**b of the interfacing portion is in the first region **52**a of the low index material **51**, and directly contacts the LOE **12** at the surface **14**b so as to form an interface between the low index material **51** and the surface **14**b of the LOE **12**. The image illumination that is injected into the LOE **12** is thus guided (i.e., propagates) by TIR at the major external surfaces **14**a, **14**b, and by equivalence is guided by TIR at the interfaces between the low index material **51** and the surfaces **14**a, **14**b.

Each of the regions **52**a, **52**b of the low index material **51** has an associated thickness. Specifically, the region **52**a has an associated thickness $\mathbf{T}_1$ that is measured between the surface **14**a (and equivalently the contact portion **53**a of the interfacing portion) and an external surface **54**a of the low index material **51** of the capsule **50**. Similarly, the region **52**b has an associated thickness $\mathbf{T}_2$ that is measured between the surface **14**b (and equivalently the contact portion **53**b of the interfacing portion) and the external surface **54**b of the low index material **51** of the capsule **50**.

Similar principles apply in cases where there is direct contact of the low index material at one or more of the other surfaces **15**a, **15**b, **16**a, **16**b of the LOE **12**. For example, the low index material may have additional interfacing portions that directly contact the remaining surfaces **15**a, **15**b, **16**a, **16**b of the LOE **12**. These additional interfacing portions are in regions of the capsule **50**, parts of which may overlap with the regions **52**a, **52**b.

It is noted that although the external surfaces of the capsule **50** (e.g., surface **54**a, surface **54**b, and other external surfaces which are not labeled in the drawings) are shown as planar surfaces, one or more (and in some cases all) of the external surfaces of the capsule can be curved or otherwise non-planar surfaces.

Parenthetically, the dimensions of the LOE **12** and the capsule **50**, including the thicknesses of the two regions **52**a, **52**b, are exaggerated for clarity in the drawings in order to better explain the principles of the present invention. Generally speaking, the thickness of the low index material **51** at the regions **52**a, **52**b can be as small as 2 μm and can be as large as permitted by optical design and manufacturing constraints. However, in certain embodiments the thickness of the low index material **51** preferably does not exceed 100 μm, i.e., the thickness of the low index material **51** is preferably in a range between 2 μm to 100 μm. In fact, it may be particularly advantageous to keep the thickness of the two regions **52**a, **52**b relatively small, more preferably in a range between 2 μm to 20 μm, and even more preferably in a range between 2 μm to 10 μm, which can increase optical performance while at the same time reduce the overall bulk of the optical device. Preferably, the thickness of the low index material **51** at the surfaces **14**a, **14**b is sufficiently small such that surface patterns of the low index material **51** follow blemish patterns at the surfaces **14**a, **14**b. These blemish patterns are typically micron-level imperfections at the surfaces **14**a, **14**b, for example in the form minor indentations along various portions of the surfaces **14**a, **14**b, and may emerge during the manufacturing process of the LOE **12**, for example during polishing stages. The blemish patterns may result in a proportion of intensity of the image illumination that is TIR-guided through the LOE **12** escaping out of the LOE **12**. If the low index material **51** is too thick, image illumination that escapes the LOE **12** may be reflected by the low index material back into the LOE **12** at unwanted angles, potentially resulting in ghost images and reducing optical performance. By making the low index material thin enough, more preferably in a range between 2 μm to 20 μm, and even more preferably in a range between 2 μm to 10 μm, surface patterns of the low index material will follow the blemish patterns of the LOE surfaces **14**a, **14**b, such that TIR-guided illumination that escapes the LOE **12** through the surfaces **14**a, **14**b most often also escape out of the low index material so as not to be reintroduced back into the LOE **12**.

It is noted that the above-mentioned thickness ranges of the low index material **51** can also be expressed as a percent of the LOE thickness (measured in the y-dimension between the surfaces **14**a, **14**b). In preferred embodiments, the thickness of the LOE **12** is typically in a range of 0.6 mm to 1.5 mm (600 μm to 1500 μm). Thus, the low index material **51** thickness ranges of greater than 2 μm, preferably between 2 μm to 100 μm, more preferably between 2 μm to 20 μm, and even more preferably between 2 μm to 10 μm respectively correspond to: greater than 0.13% of the thickness of the LOE, preferably between 0.13% to 16.67% of the thickness of the LOE, more preferably between 0.13% to 3.33% of the thickness of the LOE, and even more preferably between 0.13% to 1.67%of the thickness of the LOE.

Generally speaking, the capsule **50** can be formed from various types of transparent low index materials. Such transparent materials include, but are not limited to, bulk materials (such as glass or polymers), optical adhesives, dielectric materials, polymer materials (such polymer resin), and the like. All of these materials can be directly attached (i.e., directly bonded) to the LOE **12** at the surfaces **14**a, **14**b using various known techniques which facilitate direct attachment without use of any intermediate materials or layers between the low index material **51** and the surfaces **14**a, **14**b.

In certain embodiments, one or more layers of the low index material **51** can be directly attached to the surfaces **14**a, **14**b. This may be particularly applicable in embodiments in which the low index material is implemented as a low index optical adhesive, which can also easily accommodate attachment of additional optical components or elements to the LOE.

In other embodiments, it may be preferable to provide a single thin layer of the low index material. This may be particularly applicable in embodiments in which the low index material is implemented as a low index dielectric material or a low index polymer.

In yet further embodiments, two or more low index materials can be deployed at different regions of the LOE so as to cooperate to encapsulate the LOE. Such embodiments are of particular advantage in situations in which the LOE provides aperture expansion two dimensions, as will be discussed in subsequent sections of the present disclosure.

The technique used to attach / bond the low index material **51** to the surfaces **14**a, **14**b may depend on the type of low index material used. For example, if a bulk material is used, sonication or a heat treatment bonding process can be used to directly attach the bulk material to the surfaces **14**a, **14**b. In this respect, within the context of the present disclosure, bulk material refers to any solid-state material, including, for example, glass or polymer, that can be attached directly to the surfaces **14**a, **14**b of the LOE **12** using any process (e.g., sonication, heat treatment, and the like) that induces direct bonding without any intermediate materials present between the solid-state material and the LOE **12**.

It is noted that the major surfaces **14**a, **14**b of the LOE **12**, as well as the surfaces **54**a, **54**b of the capsule **50**, are preferably polished so as to improve optical quality. The polishing can be performed using any polishing tool or apparatus known in the art.

The process by which the LOE **12** is encapsulated by the capsule **50** is referred to herein as an encapsulation process. The encapsulation process can be performed using various techniques that are known in the art, including, but not limited to, dip-coating, spin coating, bonding, and molding. Dip-coating and spin coating are both industrial coating processes that are well-known in the art of substrate fabrication and processing. Bonding techniques have been discussed above,

and are particularly suitable when the low index material **51** is a solid-state (bulk material). Molding techniques, such as injection molding, may be particularly useful in embodiments in which the low index material **51** is implemented as a polymer or polymer resin. In such embodiments, the LOE **12** can be inserted into a mold that defines the shape of the capsule, and the low index material, such polymer resin, can then be provided (e.g., injected) into the mold and then left to cure until set and then the encapsulated LOE can be removed from the mold.

In certain scenarios, image illumination propagating through the LOE **12**, or illumination from an external scene, may impinge on portions of the LOE, such as one or more of the other surfaces **15**a, **15**b, **16**a, **16**b of the LOE **12**, which may cause scattering of part of the illumination. This scattered illumination may, in some cases, reach the user's eye, for example via deflection by the optical coupling-out configuration **30**. In order to mitigate and preferably altogether prevent light scattering effects, certain embodiments of the present invention provide a layer (or layers) of an opaque material, such as light-absorbing paint (e.g., black paint), at the perimeter edges **15**a, **15**b, **16**a, **16**b of the LOE **12**. As a result, when illumination impinges on the perimeter edges **15**a, **15**b, **16**a, **16**b that would otherwise scatter, the illumination is preferably absorbed by the opaque material.

In certain embodiments, the opaque material coating process can be simplified by reducing the surface area of the perimeter edges **15**a, **15**b, **16**a, **16**b that is to be coated with the opaque material. Before discussing this simplification in detail, it is first noted that the LOE **12** can typically be sub-divided into an active area in which the image illumination propagates and is eventually directed toward the user, and an inactive area in which the image illumination does not propagate or in which the image illumination is not directed towards the user. The active area and the inactive area are referred to interchangeably as an "imaging area" and "non-imaging area" respectively. The imaging area can be defined by an envelope that is mapped out by all ray paths propagating within the LOE **12** deflected by the optical coupling-out configuration **30** toward the EMB. FIG. 3 illustrates a schematic front view of the LOE **12** similar to as shown in FIG. 2C, except here the LOE **12** is shown with an active area **17** (demarcated by dashed lines) and an inactive area **19**.

In certain embodiments, surface area of the perimeter edges **15**a, **15**b, **16**a, **16**b can be reduced by cutting or trimming the LOE **12** to remove substantially the entirety (i.e., all or most) of the inactive area **19**, thereby providing an LOE that contains effectively only an active area. Such an LOE **12'** is illustrated in FIG. 4A. In certain embodiments, the LOE **12'** is a pre-cut LOE that is cut or trimmed from LOE **12** (here, LOE **12** is referred to also as a precursor LOE). The LOE **12** is thus modified (via cutting / trimming) to remove the inactive area **19**, thereby producing

modified LOE **12'** having only active area **17**. The modified LOE **12'** can then be polished at the surfaces **14**a, **14**b to improve optical quality. Alternatively, the surfaces **14**a, **14**b of the precursor LOE **12** can be polished prior to cutting / trimming to remove the inactive area **17**.

The modified / pre-cut LOE **12'** can then be coated with opaque material **23** at the reduced perimeter edges **15**a, **15**b, **16**a, **16**b, as illustrated in FIG. 4B. Once coated with the opaque material **23**, the coated LOE **12'** can then be encapsulated by the capsule **50** (using an encapsulation process, such as any of the encapsulation processes / techniques discussed above) such that the low index material **51** of the capsule **50** is directly attached / bonded to the surfaces **14**a, **14**b of the LOE. In certain embodiments, the low index material **51** is also directly attached / bonded to the opaque material **23** at the perimeter edges **15**a, **15**b, **16**a, **16**b. FIGS. 4C and 4D show different views of the coated LOE **12'** by capsule **50** in which the low index material also directly contacts the perimeter edges **15**a, **15**b, **16**a, **16**b. The surfaces **54**a, **54**b of the capsule **50** can then be polished to improve optical quality of the optical device.

As illustrated in FIG. 4E, the encapsulated LOE **12'** can optionally be cut or trimmed to achieve a desired eyepiece contour. In particular, the low index material **51** of the capsule **50** can be cut or trimmed to achieve a desired shape having an eyepiece contour. This is particularly useful when the encapsulated LOE is intended to be fit as part of a near-eye display device that is implemented, for example, in an eyeglasses form factor.

In certain embodiments, the LOE **12** or **12'** can be modified in order to accommodate placement of an optical coupling-in configuration. Modification of the LOE can be accomplished by cutting / trimming the LOE (prior to encapsulation) to define a coupling-in region of the LOE. FIG. 4F shows an example of the LOE **12'** which has been further modified to include coupling-in region **25** (through which the image illumination can be injected) after encapsulation by the capsule **50**. A similar modification can be made to the LOE **12**. Alternatively, the encapsulated LOE can be modified to provide the encapsulated LOE with a coupling-in region, for example by grinding / cutting / trimming an area / portion of the capsule **50** that is located in the region that will be the coupling-in region.

It is noted that removal of the inactive area of the LOE is not an absolute requirement, and embodiments are contemplated herein in which one or more of the peripheral edges **15**a, **15**b, **16**a, **16**b of a fully intact LOE (i.e., an LOE having both active and inactive areas) are coated with opaque material.

As previously mentioned, the optical coupling-in configuration (placed at the coupling-in region) functions to inject image illumination generated by an image projector (for example the image projector **18** of FIG. 1) into the LOE for guiding by TIR. As discussed, the optical coupling-

in configuration can be appropriately designed in order to accommodate injection of image illumination at angles that include shallow angles. Design of the optical coupling-in configuration may also include appropriate design of the coupling-in region, i.e., appropriately modifying the LOE or encapsulated LOE to produce an appropriate coupling-in region that can accommodate placement of the optical coupling-in configuration.

The encapsulated LOEs according to the embodiments of the present invention provide a number of advantages over conventional unencapsulated LOEs. First, the encapsulated LOEs according to certain embodiments, for example the encapsulated LOE of FIG. 4E which includes a trimmed LOE **12'** having only an active area and a capsule **50** trimmed to fit an eyepiece contour, are lighter in weight than their conventional unencapsulated LOE counterparts. Another advantage is that the encapsulated LOEs provide direct mechanical contact of functional elements such as eyeglass frames. Besides such mechanical advantages, the encapsulated LOEs according to embodiments of the present invention provide certain optical advantages over convention unencapsulated LOEs. Some notable optical advantages are the ability to attach additional optical elements, such as lenses, protective films, ghost image reducing coatings / films and the like, directly to the capsule **50** an in association with one of the major surfaces **14**a, **14**b without adversely affecting conditions of TIR.

Turning now to FIGS. 5A – 8B, there are illustrated examples of encapsulated LOEs having various additional optical elements attached thereto. In all of the examples, a first optical element (**72**a/**74**a/**76**a/**78**a) is directly attached to the capsule **50** at the surface **54**a so as to be deployed in association with the major surface **14**a (i.e., in facing relation to the user's eye), and a second optical element (**72**b/**74**b/**76**b/**78**b) is directly attached to the capsule **50** at the surface **54**b so as to be deployed in association with the major surface **14**b (i.e., facing away from the user's eye, i.e., on the back side of the LOE). The direct attachment of the optical elements **72**a/**74**a/**76**a/**78**a, **72**b/**74**b/**76**b/**78**b to the surfaces **54**a, **54**b can be provided, for example, via adhesive bonding. In embodiments in which the capsule **50** is formed from a low index optical adhesive, the low index optical adhesive (having thickness T_1 and T_2) can also be used to bond the optical elements **72**a/**74**a/**76**a/**78**a, **72**b/**74**b/**76**b/**78**b to the LOE at the surfaces **14**a, **14**b.

The first optical element **72**a/**74**a/**76**a/**78**a can be designed and deployed so as to extend across part, most, or all of the surface **54**a in the lateral direction (x-dimension in the drawings) and the transverse direction (z-dimension in the drawings). Similarly, the second optical element **72**b/**74**b/**76**b/**78**b can be designed and deployed so as to extend across part, most, or all of the surface **54**b in the lateral direction and the transverse direction.

Turning now to FIGS. 5A and 5B, there is shown a first example of optical elements in which the first optical element **72**a is in the form of a lens (which may be a prescription lens, i.e., an ophthalmic lens), and the second optical element **72**b is in the form of a protective film (i.e., a safety protective film, such as thin optical protective films).

The lens **72**a can be designed to apply positive or negative optical power, and depending on the design and deployment location of the lens, can apply such optical power to illumination from an external scene that is viewable by the user through the surfaces **14**a, **14**b and may also apply such optical power to the image illumination coupled-out from the LOE **12** e.g., rays **32**A, **32**B in FIG. 1). In the illustrated example, the lens **72**a is a plano-convex and thus applies positive power. In addition, the lens **72**a is shown as partially extending across the surface **54**a in the lateral direction and fully extending across the portion of the LOE **12** that contains the partially reflecting surfaces **30**. Thus, in the illustrated example the lens **72**a applies positive optical power to light from the external scene as well as image illumination that is coupled-out of the LOE **12** by the partially reflecting surfaces **30**.

The protective film **72**b is shown as fully extending across the surface **54**b in both lateral and transverse directions. The film **72**b can be a protective safety film that protects the LOE **12** from damage, for example chipping, shattering, breaking. The film **72**b may also be a barrier film (available, for example from 3M) that provides an anti-scratch or scratch-resistant coating, and/or protection against dirt or other particulates or contamination from coming into contact with the LOE.

With reference to FIGS. 6A and 6B, there is shown a second example of optical elements in which both the first optical element **74**a and the second optical element **74**b are implemented as a protective film (similar to the optical element **72**b in FIGS. 5A and 5B). In this example, the films **74**a, **74**b extend across the entirety of the surfaces **54**a, **54**b in both lateral and transverse directions.

FIGS. 7A and 7B illustrate a third example of optical elements. In this example, the first optical element **76**a is implemented as a first lens, and the second optical element **76**b is implemented as a second lens, each of which can apply optical power. Here, the first lens **76**a is a plano-convex (positive) lens (similar to the lens **72**a in FIGS. 5A and 5B) and the second lens **76**b is a plano-concave (negative) lens, thus the two lenses **76**a, **76**b in combination provide double optical power. In the illustrated example, the first lens **76**a extends partially across the surface **54**a in the lateral direction and fully extends across the surface **54**a in the transverse direction. Similarly, the second lens **76**b extends partially across the surface **54**b in the lateral direction and fully extends across the surface **54**b in the transverse direction.

Turning now to FIGS. 8A and 8B, there is illustrated a fourth example of optical elements. In this example, the first optical element **78**a and the second optical element **78**b are both optical power and protective lenses, meaning that both lenses provide optical power and protection functionality. Specifically, the lens **78**a, which can be a positive or negative lens but in the illustrated example is shown as a plano-convex (positive) lens (similar to lenses **72**a, **76**a), has a protective film or coating (having properties akin to the films **72**b, **74**a, **74**b) applied thereto. Similarly, the lens **78**b, which can be a positive or negative lens but in the illustrated example is shown as a plano-concave (negative) lens (similar to lens **76**b), has a protective film or coating (having properties akin to the films **72**b, **74**a, **74**b) applied thereto. In the illustrated example, the lenses **78**a, **78**b fully extend across the respective surfaces **54**a, **54**b in the transverse direction, but only partially extend across the respective surfaces **54**a, **54**b in the lateral direction.

It is emphasized that the configurations illustrated in FIGS. 5A – 8B are merely an exemplary subset of possible configurations envisioned according to embodiments of the present invention, and other configurations, including configurations having combinations of multiple optical elements deployed in association with both of the major surfaces **14**a, **14**b and configurations having only one of the major surfaces **14**a, **14**b having one or more optical elements deployed in association therewith, fall within the scope of the present invention. For example, embodiments are contemplated in which a protective film is applied at the surface **54**a (similar to as in FIGS. 6A and 6B) and a lens (for example a negative lens) is applied at the surface **54**b.

Although the embodiments described thus far have pertained to LOEs having an optical coupling-out configuration **30** implemented as a set of mutually parallel partially reflecting internal surfaces at least partially traversing the LOE and oblique to the surfaces **14**a, **14**b (i.e., facets deployed within the LOE), the set partially reflecting surfaces is merely illustrative of one non-limiting implementation of an optical coupling-out configuration, and other optical coupling configurations can be used to couple image illumination out of the LOE **12**. The optical coupling-out configuration may be any optical coupling arrangement which deflects part of the incident image illumination already propagating within the LOE **12** by TIR to an angle such that the deflected part of the image illumination exits the LOE **12**. Other examples of such suitable optical coupling arrangements include, but are not limited to, one or more diffractive optical elements (e.g., diffractive gratings) deployed on either of the surfaces **14**a, **14**b (most suitably used when the optical coupling-in configuration is implemented as one or more diffractive elements), and a beamsplitter arrangement.

The embodiments described thus far have pertained to encapsulation of LOEs that are configured to perform aperture expansion in one dimension (approximately in the x-dimension in

the arbitrarily labeled coordinate system used in the drawings). However, encapsulation of LOEs that perform two-dimensional aperture expansion using the encapsulation methodologies / techniques described above also falls within the scope of the present invention. In fact, the encapsulation methodologies described herein may in certain cases be more applicable to LOE architectures that perform two-dimensional aperture expansion. Various solutions for LOE-based optical devices that perform two-dimensional aperture expansion have been developed over the years, including two exemplary classes of solutions developed by Lumus Ltd (Israel), each of which is based on two sets of partially reflective surfaces (i.e., two sets of optical coupling configurations) within two respective regions of an LOE (implemented as one or more light-transmitting substrates) that each deflect a proportion of propagating image illumination.

In one of the exemplary classes of solutions developed by Lumus, and described in various publications, including, for example, PCT publication no. WO 2020/049542, two-dimensional aperture expansion is achieved using what is referred to as "compound LOEs". In general terms, these compound LOEs employ two regions, each of which is a parallel-faced slab of transparent (i.e., light-transmitting) material for facilitating the propagation of collimated image illumination by TIR at parallel major external surfaces, and each of which includes an optical coupling configuration (for example a set of mutually parallel partially reflecting internal surfaces (i.e., facets deployed within the LOE) or diffractive elements), which redirect the image illumination while achieving expansion of the optical aperture.

In another of the exemplary classes of solutions, also developed by Lumus, and described in various publications, including, for example, US Patent No. 10,133,070, two-dimensional aperture expansion is achieved utilizing a first rectangular LOE optically coupled with a second slab-type LOE, each of which supports propagation of image illumination by internal reflection. In general terms, these rectangular LOE based solutions also employ two regions, the first of which includes the rectangular LOE which is formed as an elongated substrate having two pairs of planar parallel major external surfaces that form a rectangular cross-section. The rectangular LOE supports propagation of image illumination by total internal reflection at the two pairs of major external surfaces (referred to as four-fold total internal reflection). The second region includes the slab-type LOE, which is optically coupled with the rectangular LOE, and which has a form similar to the LOE of FIG. 1. In other words, the second slab-type LOE has a pair of major parallel surfaces and a set of internal partially reflective surfaces (facets) inclined oblique to the major parallel surfaces. The rectangular LOE also has a set of parallel facets angled obliquely to the direction of elongation of the rectangular LOE, which deflects a proportion of the image illumination that propagates through the rectangular LOE into the second LOE so as to be guided through the second

LOE by TIR at the pair of parallel major surfaces of the second LOE. A proportion of the image illumination that propagates through the second LOE is deflected by the facets of the second LOE so as to be coupled out of the second LOE toward the eye of the observer.

Accordingly, the optical coupling-out configuration **30** described within the context of one-dimensional aperture expansion can more generally be referred to as an optical coupling configuration **30** that deflects a proportion of the image illumination that is guided within the LOE, and LOE architectures that performs two-dimensional aperture expansion can include two (or more) such optical coupling configurations each for deflecting image illumination propagating through LOE regions by TIR. In embodiments in which the LOE is configured to perform aperture expansion in one dimension only, the optical coupling configuration **30** deflects the proportion of guided image illumination out of the LOE towards the user.

Bearing the above in mind, the following paragraphs describe embodiments of at least partially encapsulated two-dimensional aperture expanding LOEs. First, embodiments of an at least partially encapsulated compound LOE will be described, and then embodiments of an at least partially encapsulated rectangular LOE based arrangement will be described.

Referring now to FIGS. 9A and 9B, there is shown different views of an example of an optical device **110** having an encapsulated compound LOE **120** having two optical coupling configurations **131**, **132** located in two respective regions of the LOE, each of which deflects propagating image illumination. The LOE **120** is formed as a slab of transparent (i.e., light-transmitting) material having a pair of parallel major external surfaces (faces) **124**a, **124**b, and has a first region **121** (also referred to herein as "LOE1" which is demarcated by dashed lines in FIG. 9A) containing the first optical coupling configuration **131** and a second region (also referred to herein as "LOE2" which is demarcated by dashed lines in FIG. 9A) containing the second optical coupling configuration **132**. In the non-limiting example embodiment illustrated in the drawings, the first optical coupling configuration **131** is implemented as a first set of planar mutually-parallel partially-reflecting internal surfaces (facets) having a first orientation, and the second optical coupling configuration **132** is implemented as a second set of planar mutually-parallel partially-reflecting internal surfaces (facets) having a second orientation non-parallel to the first orientation. It should be noted, however, that the optical coupling configurations **131**, **132** can also be implemented as diffractive optical elements (e.g., diffractive gratings) deployed on either of the surfaces **124**a, **124**b.

Parenthetically, in certain embodiments the general steps for producing optical devices having an encapsulated compound LOE are similar to those used for producing optical devices having encapsulated LOEs that perform one-dimensional aperture expansion. In such

embodiments, these steps generally include obtaining the LOE, and then at least partially encapsulating the obtained LOE by directly attaching the low index material to the major external surfaces of the LOE. As in the one-dimensional embodiments, the low index material may extend across the entirety of the length of the major external surfaces (full encapsulation) or may extend across the vast majority of the length of the major external surfaces (partial encapsulation). Obtaining the LOE may, in certain embodiments, include fabricating the LOE. Methods for fabricating compound LOEs have been described extensively in various publications by Lumus Ltd. (Israel), including, for example, in the aforementioned PCT publication no. WO 2020/049542. In other embodiments, the encapsulation step may be performed as an additional step of the compound LOE fabrication process.

In embodiments in which the optical coupling configurations **131**, **132** are implemented as sets of facets (as shown in the drawings), the first orientation generally refers to the facets **131** being inclined obliquely to the direction of propagation image illumination, and the second orientation refers to the facets **132** being non-parallel to the facets **131** and also being inclined obliquely to the surfaces **124**a, **124**b. In one set of non-limiting examples, the first orientation can also be such that the facets **131** are orthogonal to the major surfaces **124**a, **124**b, while in another set of non-limiting examples the first orientation can also be such that the facets **131** are obliquely angled relative to the major surfaces **124**a, **124**b.

The mutually-parallel major external surfaces **124**a, **124**b extend across the first and second regions **121** and **122** such that both the first set of partially-reflecting surfaces **131** and the second set of partially-reflecting surfaces **131** are located between the major external surfaces **124**a, **124**b.

Image illumination, represented here schematically by sample rays **20**, corresponding to a collimated image generated by image projector **18**, propagates within the first region **121** of the LOE **120** by TIR at the surfaces **124**a, **124**b. The first optical coupling configuration **131** deflects part of the image illumination from a first direction of propagation trapped / guided by TIR within the first region **121** of the LOE **120** to a second direction of propagation, also trapped / guided by TIR within the LOE **120**. The deflected image illumination (represented here schematically by sample rays **21**) then passes from the first region **121** into the second region **122**, in which the second optical coupling configuration **132** deflects part of the TIR-guided image illumination so as to progressively couple a proportion of the image illumination (represented schematically in FIG. 9B as sample rays **32**) out of the LOE **120** and towards the eye **36** of the observer / user located within the EMB, thereby achieving a second dimension of optical aperture expansion.

It is noted that in drawings corresponding to the compound LOE embodiments, only the in-plane propagation directions of the rays are illustrated during propagation within the LOE, but

the rays actually follow a zigzag path of repeated internal reflection from the two major external surfaces **124**a, **124**b (similar to as shown in FIG. 1), and one entire dimension of the image field of view is encoded by the angle of inclination of the rays relative to the major external surfaces, corresponding to the pixel position in the Y dimension.

The LOE **120** also includes additional external (perimeter) surfaces (edges) **125**a, **125**b, **126**a, **126**b which may or may not be pairs of parallel surfaces. It is noted that in the illustrated example, the low index material **51** of the capsule **50** is only in direct contact with parallel major surfaces **124**a, **124**b of the LOE **120** but is not in contact with the perimeter surfaces (edges) **125**a, **125**b, **126**a, **126**b of the LOE **120**. However, it should be apparent that other configurations are possible in which the low index material is in direct contact with one or more of the perimeter surfaces (edges) **125**a, **125**b, **126**a, **126**b.

In certain embodiments, the edges **125**a, **125**b, **126**a, **126**b can be coated with an opaque material to reduce scattering, similar to as described above in the context of the one-dimensional aperture expanding LOE **12**. In addition, similar to the LOE **12**, the compound LOE **120** has an active area and an inactive area. Thus, similar to as previously described in the context of the LOE **12**, a compound LOE having only an active area can be obtained (for example by trimming / cutting the compound LOE **120** to remove the inactive area), and the perimeter edges of the trimmed compound LOE can be coated with the opaque material. FIG. 10 illustrates an example of a compound LOE **120'** that has been trimmed to remove most or all of the inactive area, and in which the resulting perimeter edges **125**a, **125**b, **126**a, **126**b have been coated with opaque material **23**. In this example, the low index material **51** of the capsule **50** is also shown as being in direct contact with the coated perimeter edges **125**a, **125**b, **126**a, **126**b.

Similar to the LOE described with reference to FIGS. 5A – 8B, the LOE **120** can have additional optical elements attached thereto via direct attachment to the capsule **50** at the external surfaces **54**a, **54**b of the low index material **51**, including combinations of lenses and protective films. FIG. 11 illustrates one non-limiting example configuration in which a first optical element **82**a (represented here as a lens, e.g., an ophthalmic lens) is attached at the front surface **54**a of the capsule **50**, and a second optical element **82** (represented here as a protective film) is attached at the back surface **54**b of the capsule **50**. Although only one example configuration, in which the optical elements **82**a and **82**b are implemented as a lens and a protective film, respectively, is illustrated in the drawings, it should be clear that any of the combinations of lenses and/or protective films discussed above in the context of LOEs that perform one-dimensional aperture expansion are also applicable here in the context of LOE **120** that performs two-dimensional aperture expansion.

It is noted that although FIG. 11 shows the lens **82**a as extending along the entirety of the surface **54**a in the lateral dimension (x-dimension in the figure) so as to extend along the entirety of the major surface **124**a in the lateral dimension such that the lens **82**a is associated with portions of the major surface **124**a in each of the regions **121**, **122** of the LOE **120**, in certain cases, the dimensions of the lens **82**a may be limited such that the lens **82**a extends only across a portion of the surface **54**a in the lateral dimension such that the lens **82**a is only associated with portions of the major surface **124**a that are in the second region **122** of the LOE **120**. This may, in certain cases, be more practical since it is in the second region **122** of the LOE **120** from which image illumination is deflected out by the facets **132**, and also through which the eye **36** can view the external scene (via the major surfaces **124**a, **124**b).

As mentioned in previous sections of the present disclosure, the thicknesses (T_1 and T_2) of the two regions **52**a, **52**b (which respectively correspond to the layer(s) of the low index material **51** of the capsule **50** extending across the length of the surfaces **124**a and **124**b) are exaggerated for clarity in the drawings in order to better explain the principles of the present invention, but it may be particularly advantageous to keep the thicknesses of the two regions **52**a, **52**b relatively small to increase optical performance while at the same time reducing the overall bulk of the optical device. Specifically, the thickness of the low index material **51** at the surfaces **124**a, **124** is preferably sufficiently small such that surface patterns of the low index material **51** follow blemish patterns at the surfaces **124**a, **124**b such that TIR-guided illumination that escapes the LOE **120** through the surfaces **124**a, **124**b most often also escape out of the low index material **51** so as not to be reintroduced back into the LOE **120**. However, situations may arise in which image illumination that deviates from the main image escapes from the LOE **120** and into one or both of the regions **52**a, **52**b and is reflected at the surface **54**a or **54**b by TIR (due to the escaped illumination impinging on the surface **54**a or **54**b at an angle of incidence greater than a critical angle defined by the refractive index of the low index material **51** and the medium surrounding the capsule **50**, which is typically air) back into the LOE **120** as scattered light. In addition, situations may arise in which light from a scene (e.g., external scene) can enter the LOE and be reflected by one of the optical coupling configurations towards the user's eye. These situations are schematically illustrated in FIG. 12, which shows an enlarged partial side view of the first region **121** of the LOE **120**. As illustrated in FIG. 12, illumination (represented schematically as thick sample ray **27**) that deviates from the main TIR-guided image **20** and escapes from the LOE **120** (via the surface **124**a) into region **52**a of the capsule **50** is reflected by TIR at the surface **54**a and then re-enters the LOE **120** (via the surface **124**a) as scattered light (represented schematically as thick sample ray **29**). Also shown is light (represented schematically as thick sample ray **31**) from

an external scene that enters the LOE **120** (via the surface **124**b) and is deflected / reflected by the optical coupling configuration **131** as reflected light (represented schematically as thick sample ray **33**) toward the user's eye **36**.

In order to mitigate scattering and unwanted reflections in the above-mentioned scenarios, certain embodiments of the present disclosure provide one or more layers of a light-absorbing material at one or more portions of the low index material **51**. With reference now to FIGS. 13A and 13B, there are shown different views of the optical device **110** having light-absorbing material **60** deployed in association with portions of the low index material **51**, preferably via direct attachment to the portions of the low index material **51**. In the illustrated example, the light-absorbing material **60**, which can be implemented for example as one or more layers of black paint, is directly deposited or coated on a minority portion (surface area) of each of the surfaces **54**a, **54**b of the low index material **51** that is directly attached to the surfaces **124**a, **124**b in the first region **121** of the LOE **120**. The minority portion of the surfaces **54**a, **54**b of the low index material **51** that is covered by the light-absorbing material **60** constitutes roughly the entire surface area of the low index material **51** that covers the area spanned by the projection of the first optical coupling configuration **131** in the xz plane, and preferably includes the surface area of the low index material **51** that extends slightly beyond this spanned area. This helps to ensure that illumination from the external scene arriving at the optical device at angles that would otherwise support entry to the LOE and deflection from the optical coupling configuration **131** are absorbed by the light-absorbing material **61**. Roughly speaking, the area of the low index material **51** that is covered by the light-absorbing material **60** includes roughly the entire surface area of the low index material **51** that covers the first region **121** of the LOE **120** and may also include some of an intermediate region of the LOE **120** between the regions **121**, **122** (or some of the second region **122**) so as to extend slightly beyond the projection of the first optical coupling configuration **131** in the xz plane. By proportion, the minority portion of the surfaces **54**a, **54**b of the low index material **51** that is covered by the light-absorbing material **60** makes up approximately 10 – 20% of the surface area of the low index material deployed at each of the surfaces **124**a, **124**b.

FIG. 14 schematically illustrates the effect of the light-absorbing material on escaped illumination (ray **27**) and scene illumination (ray **31**). As shown, illumination **27** that deviates from the main TIR-guided image **20** and escapes the LOE **120** (via the surface **124**a) into region **52**a of the capsule **50** is absorbed by the light-absorbing material **60** deployed at the surface **54**a, thereby preventing the occurrence of TIR at the surface **54**a and preventing re-entry of scattered light into the LOE **120**. Also as shown, illumination **31** from an external scene is absorbed by the light-

absorbing material **60** deployed at the surface **54**b, thereby preventing deflection / reflection of the illumination **31** by the optical coupling configuration **131** toward the user's eye.

In order to prevent Fresnel reflections or TIR reflections, the light-absorbing material **60** preferably has a refractive index that is the same as (i.e., equal to) or slightly higher than the refractive index of the low index material **51** that forms the capsule **50**. By slightly higher, it is meant that the refractive index of the light-absorbing material **60** is preferably no more than 10% larger / greater (and more preferably no more than 5% larger / greater) than the refractive index of the low index material **51** from which the capsule **50** is formed.

Since the eye **36** is located in the EMB which located in front of the second region **121** of the LOE **120**, the layer(s) of light-absorbing material **60** does/do not interfere with the user's visibility of the image illumination coupled-out by the second optical coupling configuration **131** or the user's visibility of the external scene, which is viewable through the surfaces **124**a, **124**b.

As mentioned above, in certain embodiments the capsule **50** can be formed from more than one low index material. FIG. 15 illustrates a non-limiting example of such an embodiment in which a first low index material **61** is directly attached to the portions of the surfaces **124**a, **124**b that are in the first region **121**, and a second low index material **62** is directly attached to the portions of the surfaces **124**a, **124**b that are in the second region **122**. The second low index material **62** is a transparent material, and the first low index material may or may not be a transparent material. Here, the first region **52**a of the capsule **50** is sub-divided into two sub-regions **52**a-1 and **52**a-2, and the second region **52**b of the capsule **50** is sub-divided into two sub-regions **52**b-1 and **52**b-2.The first low index material **61** is in the sub-regions **52**a-1 and **52**b-1, whereas as the second low index material **62** is in the sub-regions **52**a-2 and **52**b-2. The two low index materials **61**, **62** are adjacently placed to form the capsule, and thus cooperate to at least partially encapsulate the LOE. In other words, a part of the capsule **50** is formed from the first low index material **61**, and another part of the capsule **50** is formed from the second low index material **62**. Preferably, at each of the major external surfaces **124**a, **124**b of the LOE **120**, the external surface **62**e of the second low index material **62** that is attached to the major external surface of the LOE **120** is a continuation of the external surface **61**e of the first low index material **61** that is attached to the major external surface of the LOE **120**, thereby forming the external surfaces **54**a, **54**b of the capsule **50**.

Preferably, the two low index materials **61**, **62** have the same or similar refractive index. However, this is not an absolute requirement, and the LOE **120** can still provide two-dimensional aperture expansion despite variations in the refractive indices between the two materials **61**, **62**. For example, the first low index material **61** can have a refractive index of approximately 1.2, and the second low index material **62** can have a refractive index of 1.3.

In certain embodiments, the first low index material **61** is a transparent material. In other embodiments, the first low index material **61** is a light-absorbing material having a low refractive index, implemented, for example, as black paint with inherently low refractive index (e.g., refractive index of approximately 1.3). In such other embodiments, the first low index material **61** performs multiple functions, including, for example, i) preserving conditions of TIR at the portions of the major external surfaces **124**a, **124**b that are in the first region **121**, ii) preventing illumination from the external scene, that would otherwise enter the LOE **120** via the portions of the major external surfaces **124**a, **124**b that are in the first region **121** and deflect from the first optical coupling configuration **131**, from entering the LOE **120** by absorbing the external scene illumination, and iii) preventing TIR-guided illumination that escapes the LOE **120** through the portions of the major external surfaces **124**a, **124**b that are in the first region **121** from re-entering the LOE **120** by absorbing the scaped illumination.

It is noted that in embodiments in which the first low index material **61** is a low index light-absorbing material, the first low index material **61** preferably covers the same or similar surface area of the major external surfaces **124**a, **124**b with which the light-absorbing material **60** of FIGS. 13B and 14 is associated. In other words, the first low index material **61** preferably covers the surface area of the major external surfaces **124**a, **124**b that is spanned by, and preferably extends slightly beyond, the projection of the first optical coupling configuration **131** in the xz plane.

In addition, since the low index material **61** is itself a light-absorbing material in such other embodiments, no additional layer of light-absorbing material (for example as illustrated in FIGS. 13B and 14) may be necessary.

In certain cases, in particular embodiments in which an additional optical element (e.g., a protective film) is attached to the LOE via the low index material (or low index materials), it may be advantageous to apply an additional coating layer or layers to all or part of the exposed surfaces of the optical element to increase mechanical stability and to help block unwanted light from the external scene entering the LOE. One exemplary material that can be used for the additional coating layer(s) is anti-reflective (AR) coating, which provides rigidity (mechanical stability) and anti-reflection properties. Another exemplary material that can be used for the additional coating layer(s) is a light-absorbing material, e.g., black paint. FIGS. 16A and 16B illustrate various views of an LOE according to one non-limiting example embodiment in which a coating **63** (e.g., one or more layers of AR coating, one or more layers of black paint) is applied to portions of a protective film **82**b (e.g., a thin optical protective film) that is attached to the low index material (or materials) that is attached to one of the major external surfaces **124**b. For clarity of illustration, the optical coupling configurations **131**, **131** are not shown in FIG. 16B. Preferably, the coating **63** covers

some or all of the major surface of the film **82**b (preferably at least the portion of the major surface **83**b of the film **82**b associated with the first region **121** of the LOE **120**, for example the portion of the film **82**b that is attached to the first low index material **61**) as well as the edges of the film **82**b and the edges of the low index material (up to the intersection with the major surface **124**b of the LOE **120**). This ensures that the low index material itself is protected from the environment, thereby preventing the low index material from chipping or peeling away from the LOE. In the illustrated example, the capsule **50** is formed from two low index materials **61**, **62**, and the coating **63** covers the portion of the major surface **83**b of the film **82**b associated with the first low index material **61**. However, it should be apparent that in certain non-limiting configurations the coating **63** can also be deployed to cover the portion of the major surface **83**b of the film **82**b associated with the second low index material **62**.

In addition, it should be apparent that the deployment of the coating **63** is also suitable in situations in which a single low index material is used to form the capsule. In such configurations, the coating **63** may be deployed to cover only in the portion of the major surface of the film **82**b associated with the portion of the low index material associated with the first region **121**, or may be deployed to cover the entire major surface of the film **82**b. It is also noted that although FIGS. 16A and 16B show the coating **63** as having been deployed on the protective film **82**b that is associated with the major external surface **124**b that is opposite from the user's eye, the coating **63** can also be deployed on a protective film (that is similar to protective film **82**b) that is associated with the major external surface **124**a that is in facing relation to the user's eye (i.e., a protective film that is attached to the low index material that is attached to the major external surface **124**a, similar, for example, as the film **74**a illustrated in FIG. 6A). Such deployment of coating **63** on a protective film that is associated with the major external surface **124**b can be in addition to, or instead of, the deployment of the coating **63** on the film **82**b that is associated with the major external surface **124**b, as illustrated in FIGS. 16A and 16B.

Although the at least partially encapsulated compound LOE described herein has pertained to a particular non-limiting configuration of optical coupling configurations, other variant embodiments, employing, for example, differing imaging injection locations and geometries, non-uniform facet spacing, or introducing additional (e.g., third) sets of partially-reflecting internal surfaces, are discussed in detail in prior publications by Lumus Ltd. (Israel), particularly in the aforementioned PCT publication no. WO 2020/049542, as well as PCT publication no. WO 2020/152688 and PCT application number PCT/IL2020/051354. These additional features may all be implemented in the context of the present invention, but for conciseness, they are not addressed here in detail.

Turning now to FIGS. 17A and 17B, there is illustrated different views of an example of an optical device **200** having an at least partially encapsulated LOE **205** that performs two-dimensional aperture expansion according to another embodiment of the present invention. Here, the LOE **205** is a rectangular substrate-based architecture, and includes in a first region (or LOE section) **221** a first (rectangular) LOE **210** formed as a light-transmitting substrate having a direction of elongation (arbitrarily shown as being along the z-axis) and two pairs of major parallel external surfaces (faces) **212**a, **212**b, **214**a, **214**b that form a rectangular cross-section. A first optical coupling configuration **131**, represented here as a plurality of mutually parallel partially reflective internal surfaces (facets) **131** that at least partially traverse the LOE **210** and are inclined obliquely to the direction of elongation of the LOE **210** (i.e., the facets **131** are oblique to the surfaces **212**a, **212**b), functions to deflect image illumination propagating through the LOE **210**.

The rectangular LOE **210** is optically coupled with a second slab-type LOE **220**, in a second region (or LOE section) **222** of the LOE **205**, that is similar in structure to the LOE **12** described with reference to FIGS. 1 – 2C. Specifically, the LOE **220** is formed as a light-transmitting substrate having a pair of parallel major external surfaces **224**a, **224**b that guides image illumination through the LOE **220** by TIR at the surfaces **224**a, **224**b, and has a second optical coupling configuration **132**, represented here as a plurality of mutually parallel partially reflective internal surfaces **132** that at least partially traverse the LOE **220** and are inclined obliquely to the faces **224**a, **224**b. Preferably, the pairs of surfaces **224**a, **214**a and **224**b, **214**b are each parallel and coplanar such that the surfaces **224**a, **214**a form an apparent single surface that is parallel to an apparent single surface formed by the surfaces **224**b, **214**b.

The optical coupling between the LOEs **210**, **220**, and the deployment and configuration of the partially reflective surfaces **131**, **132** are such that, when image illumination **20** corresponding to a collimated image is coupled (injected) into the rectangular LOE **210** with an initial direction of propagation at a coupling angle oblique to both pairs of parallel faces **212**a, **212**b, **214**a, **214**b, the image advances by four-fold total internal reflection (images **a**1, **a**2, **a**3, **a**4) along the rectangular LOE **210**, with a proportion of intensity of the image reflected at the partially reflective surfaces **131** so as to be coupled into the slab-type LOE **220**, and then propagates through two-fold total internal reflection (images **b**1, **b**1) within the LOE **220**, with a proportion of intensity of the image reflected (deflected) at the partially reflective surfaces **132** so as to be directed outwards from one of the parallel faces **224**b as a visible image **32** seen by the eye **36** of the observer.

It should be understood that the concepts related to at least partial encapsulation of the compound LOEs **120 / 120'**, including at least partial encapsulation using a capsule formed from

low index material (that can include one or more transparent low index materials, or a transparent low index material that is adjacent to a light-absorbing low index material), attachment of additional optical elements to the low index material(s), deployment of additional coating layers, contour shaping to fit the shape of an eyeglass lens, and other such concepts, all as described above in the context of compound LOEs **120 / 120'**, are also applicable here in the context of rectangular-based LOE **205** unless explicitly stated otherwise. Thus, the details of the encapsulation of LOE **205** and the concepts related thereto will not be repeated here, and will only be discussed in general.

Bearing the above in mind, in general, the capsule **50** which encapsulates the LOE **205** can be formed from a single low index material (that is in direct contact with the surfaces **214**a, **214**b, **224**a, **224**b) or can be formed from a first low index material that is in direct contact with the surfaces **214**a, **214**b and a second low index material that is in direct contact with the surfaces **224**a, **224**b). In the drawings, the capsule **50** is shown as being formed from two low index materials **61**, **62**, where the first low index material **61** is in direct contact with the surfaces **214**a, **214**b and the second low index material is in direct contact with the surfaces **224**a, **224**b. In certain embodiments, such as the embodiment illustrated in FIG. 18, additional optical elements **82**a, **82**b (represented here as a lens and a protective film, respectively) can be deployed in association with the front and back faces of the LOE **205** via direct attachment to relevant portions of the low index material(s) of the capsule **50**. In the illustrated example, the lens **82**a only extends partially along the LOE **205** in the x-dimension such that the lens **82**a covers the region **222**, however similar to as discussed above, the lens **82**a may extend fully across the surfaces **214**b, **224**b in the x-dimension. As should be apparent, any of the combinations of lenses and/or protective films discussed above in the context of LOEs that perform one-dimensional aperture expansion are also applicable here in the context of LOE **205** that performs two-dimensional aperture expansion.

Parenthetically, although FIG. 17A shows a non-limiting example in which the entirety of the major external surfaces **214**a, **214**b of the rectangular LOE **210** have the first low index material **61** attached thereto, and the entirety of the major external surfaces **224**a, **224**b of the slab-type LOE **220** have the second low index material **62** attached thereto, other configurations are possible. For example, the first low index material **61** may extend down (further along the x-axis) so as to also be attached to minority portions of the major external surfaces **224**a, **224**b of slab-type LOE **220** (located in the "upper" portion of the slab-type LOE **220** that is proximate to the coupling between the two LOEs **210**, **220**).

In certain embodiments, such as the embodiment illustrated in FIG. 19, light-absorbing material **60** can be deployed in association with the low index material that is in contact with the

first region **221** (i.e., the low index material that is in contact with the surfaces **214**a, **214**b of the rectangular LOE **210**). In other embodiments, the low index material that is in contact with the surfaces **214**a, **214**b (e.g., the low index material **61** in FIG. 17A) can be implemented as a light-absorbing material having a low refractive index, such as black paint with inherently low refractive index. Although not illustrated in the drawings, an additional coating (e.g., AR, black paint) can be applied to a protective film attached to the low index material in the first region **221** of the LOE **205**, similar to as illustrated in FIGS. 16A and 16B.

It is noted that one aspect of encapsulation of the LOE **205** that may be different from the encapsulation of LOE **120 / 120'** relates to the surfaces **212**a, **212**b. In general, for all of the LOEs disclosed herein, the optical properties of any pair major external surfaces that reflect illumination by TIR should be the same. Since the rectangular LOE **210** guides light by four-fold total internal reflection, the optical properties of the opposing surfaces **212**a, **212**b should be the same such that illumination that impinges at the surfaces **212**a, **212**b at a given angle is reflected to the same angle by the surfaces **212**a, **212**b. Thus, if the low index material of the capsule **50** is also directly attached to the surface **212**a (such as low index material **61** or **62** illustrated in FIGS. 17A – 19), care should be taken to ensure that the matching optical properties of the opposing surfaces **212**a, **212**b are preserved such that the range of angles reflected by TIR at the surface **212**b is the same range of angles reflected by TIR at the surface **212**a.

In certain embodiments, the general steps for producing optical devices having an encapsulated rectangular LOE based arrangement are similar to those used for producing optical devices having encapsulated compound LOEs and LOEs that perform one-dimensional aperture expansion. In such embodiments, these steps generally include obtaining the rectangular LOE based arrangement (i.e., obtaining LOE **205**), and then encapsulating the LOE **205** by directly attaching the low index material to the major external surfaces **214**a, **214**b (and preferably also the surface **212**a) of the LOE **210** and the major external surfaces **224**a, **224**b. Obtaining the LOE may, in certain embodiments, include fabricating the LOE **205**. Methods for fabricating encapsulated rectangular LOE based arrangement have been described extensively in various publications by Lumus Ltd. (Israel), including, for example, in the aforementioned US Patent No. 10,133,070, and in co-pending PCT application no. PCT/IL2022/050500. In certain embodiments, the encapsulation step may be performed as an additional step of the LOE fabrication process.

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.

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

Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

WHAT IS CLAIMED IS:

1. An optical device for directing image illumination towards a user for viewing, the optical device comprising:

a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including a plurality of surfaces including a pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces, the LOE further including at least one optical coupling configuration for deflecting a proportion of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces; and

an optical material including at least one transparent material directly attached to the LOE at least at the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate the LOE, the optical material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces,

wherein the image illumination that is guided within the LOE by total internal reflection at the major external surfaces is incident to the major external surfaces at a range of angles greater than a critical angle defined by the first and second refractive indices, wherein the angles greater than the critical angle include shallow angles measured relative to the major external surfaces.

2. The optical device of claim 1, wherein the at least one transparent material is formed from a solid-state material.

3. The optical device of claim 1, wherein the at least one transparent material is formed from one or more layers of optical adhesive.

4. The optical device of claim 1, wherein the at least one transparent material is a thin coating layer of a polymer or dielectric material.

5. The optical device of claim 1, wherein the optical material has a thickness that is sufficiently small such that surface patterns of the optical material follow blemish patterns at the major external surfaces.

6. The optical device of claim 5, wherein the thickness is in a range from 2 μm to 20 μm.

7. The optical device of claim 1, wherein the first refractive index is in a range from 1.5 to 1.8.

8. The optical device of claim 1, wherein the second refractive index is in a range from 1.3 to 1.4.

9. The optical device of claim 1, wherein the at least one optical coupling configuration includes exactly one optical coupling configuration that deflects the proportion of the image

illumination that is guided within the LOE by total internal reflection at the major external surfaces out of the LOE towards the user.

10. The optical device of claim 9, wherein the optical coupling configuration is implemented as a plurality of mutually parallel partially reflecting surfaces deployed within the LOE and oblique to the major external surfaces.

11. The optical device of claim 9, wherein the optical coupling configuration is implemented as at least one diffractive element associated with one of the major external surfaces.

12. The optical device of claim 1, wherein the LOE includes a first region and a second region, and wherein the at least one optical coupling configuration includes a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region.

13. The optical device of claim 12, wherein the first optical coupling configuration is implemented as a first plurality of mutually parallel partially reflecting surfaces having a first orientation, and wherein the second optical coupling configuration is implemented as a second plurality of mutually parallel partially reflecting surfaces having a second orientation that is non-parallel to the first orientation.

14. The optical device of claim 12, wherein the first optical coupling configuration is implemented as a first at least one diffractive element associated with one of the major external surfaces, and wherein the second optical coupling configuration is implemented as a second at least one diffractive element associated with one of the major external surfaces.

15. The optical device of claim 12, further comprising: a light-absorbing material deployed in association with one or more portions of the at least one transparent material in the first region.

16. The optical device of claim 15, wherein the light-absorbing material has a refractive index that is equal to the first refractive index or no more than 10% greater than the first refractive index.

17. The optical device of claim 1, further comprising: at least one optical element attached to the at least one transparent material.

18. The optical device of claim 17, wherein the at least one optical element includes: a lens attached to a first portion of the at least one transparent material that is directly attached to a first

of the major external surfaces, and a protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

19. The optical device of claim 17, wherein the at least one optical element includes: a first lens attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a second lens attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

20. The optical device of claim 17, wherein the at least one optical element includes: a first protective film attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a second protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

21. The optical device of claim 1, wherein the LOE is a pre-cut LOE that is cut from a precursor LOE prior to the optical material being directly attached to the LOE such that the LOE includes substantially only an active area in which the image illumination propagates, and wherein one or more perimeter edges of the LOE are coated with at least one layer of opaque material.

22. A method for fabricating an optical device that directs image illumination towards a user for viewing, the method comprising:

obtaining a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including a plurality of surfaces including a pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces, the LOE further including at least one optical coupling configuration for deflecting a proportion of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces, wherein the image illumination that is guided within the LOE by total internal reflection at the major external surfaces is incident to the major external surfaces at a range of angles greater than a critical angle defined by the first and second refractive indices, wherein the angles greater than the critical angle include shallow angles measured relative to the major external surfaces; and

directly attaching an optical material that includes at least one transparent material to the LOE at least at the major external surfaces such that the optical material directly contacts the major external surfaces and at least partially encapsulates the LOE, the optical material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces.

23. The method of claim 22, wherein the LOE includes an active area in which the image illumination propagates and an inactive area in which the image illumination does not propagate or in which the image illumination is not directed towards the user, the method further comprising: prior to directly attaching the optical material to the LOE:

modifying the LOE to remove the inactive area such that substantially only the active area of the LOE remains, thereby producing a modified LOE, and

coating one or more perimeter edges of the modified LOE with at least one layer of opaque material.

24. The method of claim 23, wherein the optical material is additionally directly attached to the opaque material at the one or more perimeter edges of the modified LOE.

25. The method of claim 24, further comprising: cutting or trimming the optical material to achieve a contour of an eyepiece.

26. The method of claim 22, further comprising: polishing the at least one transparent material.

27. The method of claim 22, further comprising: attaching at least one optical element to the at least one transparent material.

28. The method of claim 27, wherein the at least one optical element includes: a lens attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

29. The method of claim 27, wherein the at least one optical element includes: a first lens attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a second lens attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

30. The method of claim 27, wherein the at least one optical element includes: a first protective film attached to a first portion of the at least one transparent material that is directly attached to a first of the major external surfaces, and a second protective film attached to a second portion of the at least one transparent material that is directly attached to a second of the major external surfaces.

31. The method of claim 22, wherein the LOE includes a first region and a second region, and wherein the at least one optical coupling configuration includes a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first

optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region, and wherein the method further comprising: deploying a light-absorbing material in association with one or more portions of the at least one transparent material in the first region.

32. The method of claim 31, wherein the light-absorbing material has a refractive index that is equal to the first refractive index or no more than 10% greater than the first refractive index.

33. The method of claim 22, wherein directly attaching the at least one transparent material to the LOE includes performing a process selected from the group consisting of: dip-coating, spin coating, bonding, and molding.

34. An optical device for directing image illumination towards a user for viewing, the optical device comprising:

a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including:

a plurality of surfaces including at least one pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces,

a first region and a second region, and

a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region;

a transparent material directly attached to the LOE at least at the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate the LOE, the transparent material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces; and

a light-absorbing material deployed in association with one or more portions of the transparent material in the first region.

35. An optical device for directing image illumination towards a user for viewing, the optical device comprising:

a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including:

a plurality of surfaces including at least one pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces,

a first region and a second region, and

a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region;

a light-absorbing material directly attached to the LOE at the major external surfaces in the first region so as to be in direct contact with the major external surfaces in the first region; and

a transparent material directly attached to the LOE at the major external surfaces in the second region so as to be in direct contact with the major external surfaces in the second region,

wherein the transparent material and the light-absorbing material cooperate to at least partially encapsulate the LOE, and wherein each of the transparent material and the light-absorbing material has a refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces.

36. An optical device for directing image illumination towards a user for viewing, the optical device comprising:

a light-guide optical element (LOE) formed from a light-transmitting material having a first refractive index, the LOE including:

a plurality of surfaces including at least one pair of parallel major external surfaces for guiding image illumination within the LOE by total internal reflection at the major external surfaces,

a first region and a second region, and

a first optical coupling configuration located in the first region and a second optical coupling configuration located in the second region, the second optical coupling configuration configured for deflecting a part of the image illumination that is guided within the LOE by total internal reflection at the major external surfaces from the first region to the second region out of the LOE towards the user, and the first optical coupling configuration configured for deflecting a part of the image illumination that is guided within the first region by total internal reflection at the major external surfaces towards the second region;

at least one transparent material directly attached to the LOE at least at the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate

the LOE, the at least one transparent material having a second refractive index that is less than the first refractive index so as to maintain conditions of total internal reflection at the major external surfaces;

at least one protective film associated at least with a portion of the at least one transparent material such that the at least one protective film is associated with a portion of at least one of the major external surfaces in the first region; and

a coating deployed on at least a portion of the at least one protective film such that the coating is associated with the portion of the at least one transparent material.

37. The optical device of any of claims 34 to 36, wherein the first region is configured as a first LOE section having two pairs of parallel major external surfaces forming a rectangular cross-section such that the image illumination propagates through the first LOE section by total internal reflection at the two pairs of parallel major external surfaces.

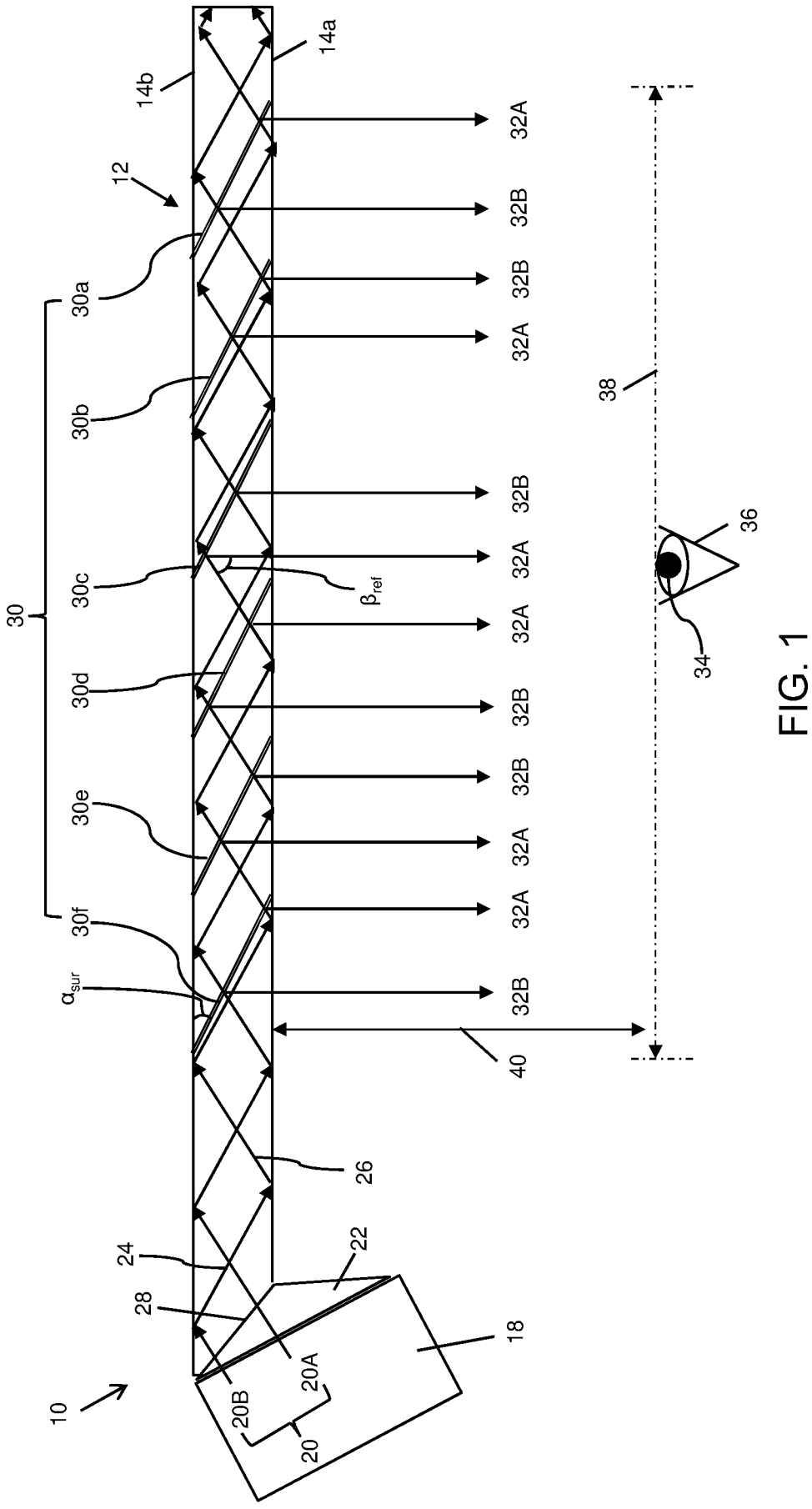

10
12
14a
14b
18
20
20A
20B
22
24
26
28
30
30a
30b
30c
30d
30e
30f
32A
32B
34
36
38
40
α_{sur}
β_{ref}

FIG. 1

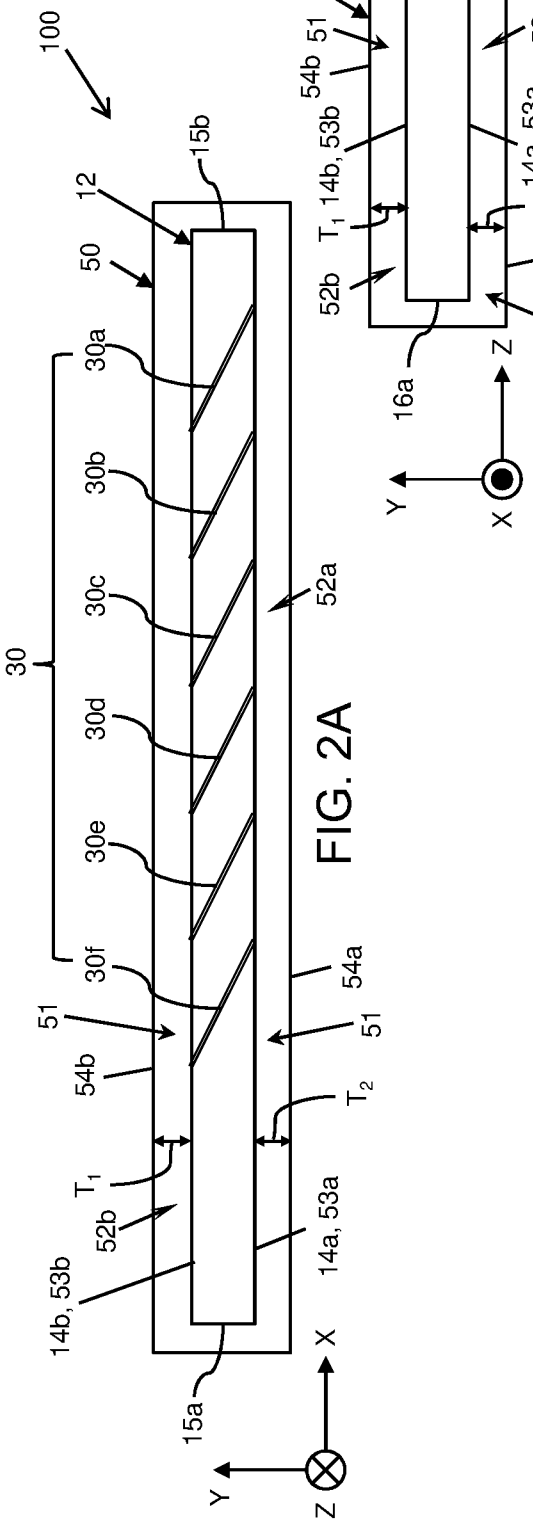


FIG. 2A

FIG. 2B

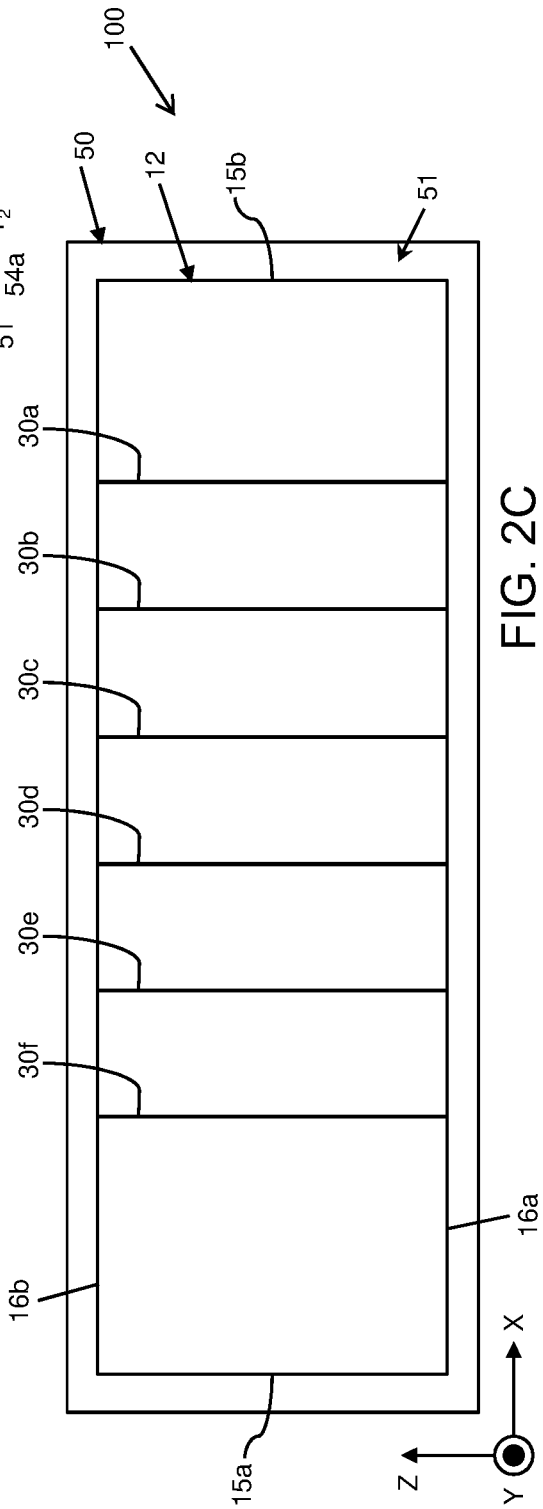


FIG. 2C

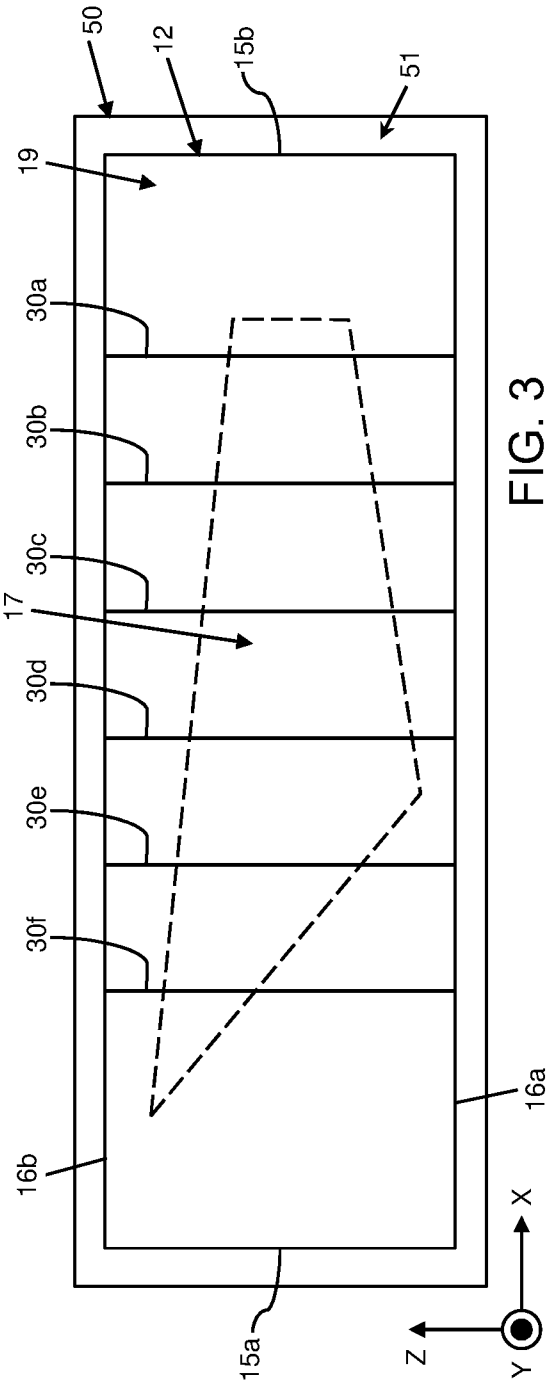


FIG. 3

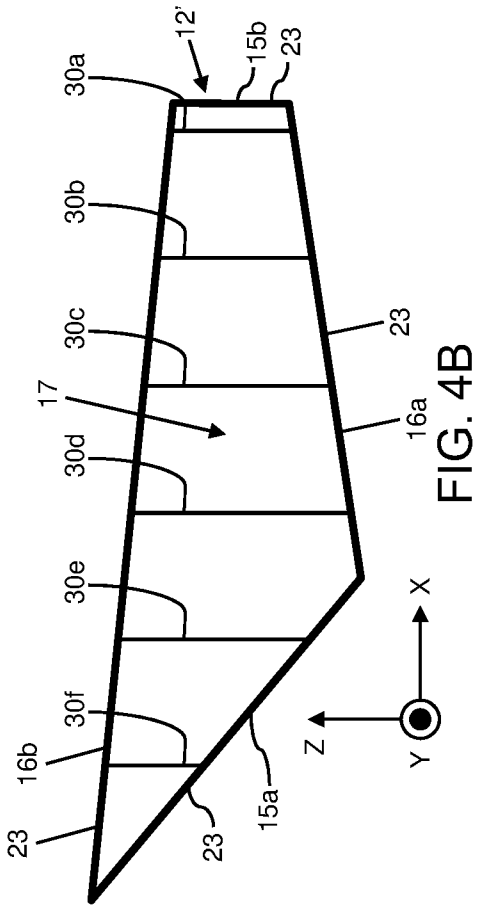


FIG. 4B

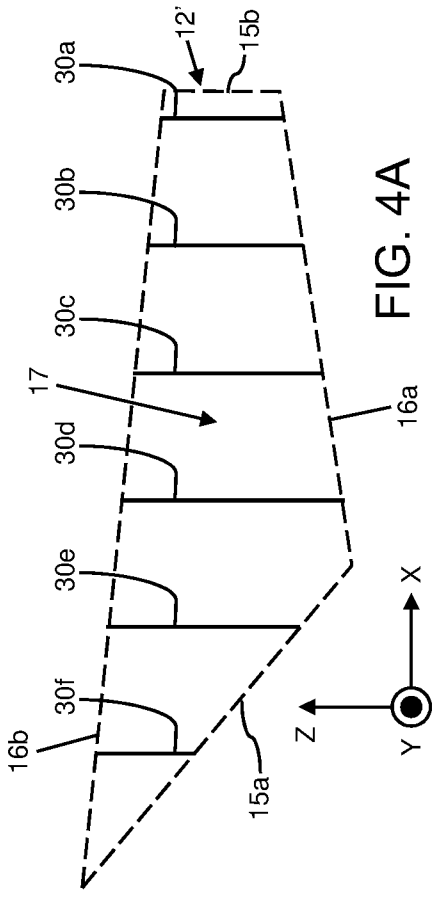


FIG. 4A

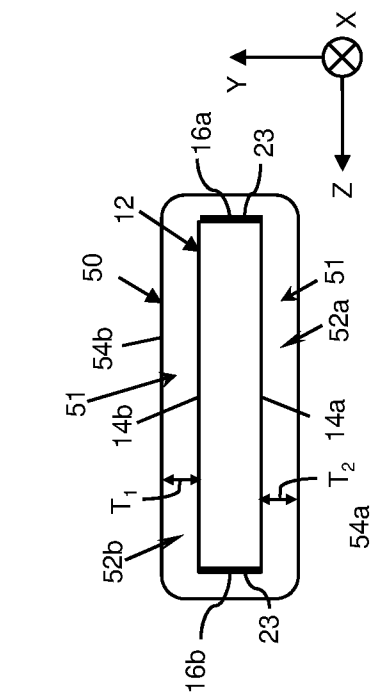


FIG. 4D

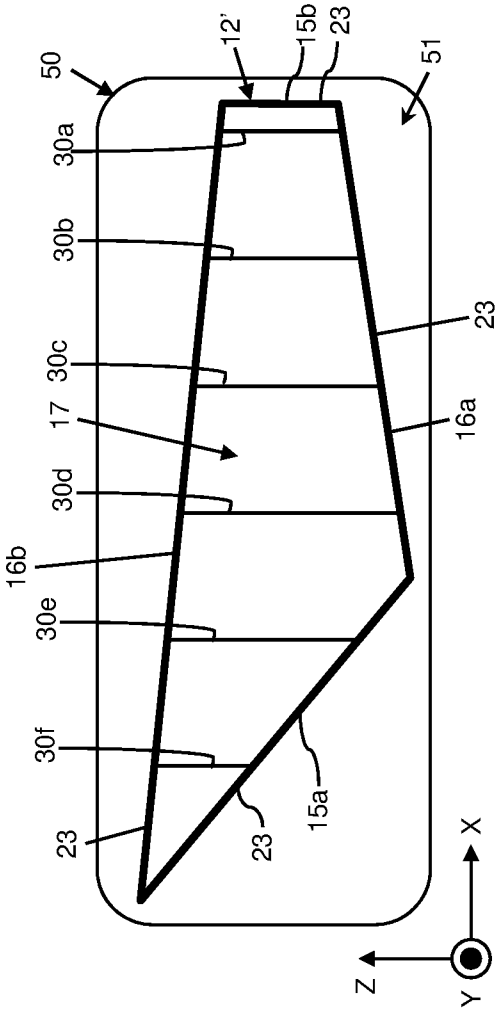


FIG. 4C

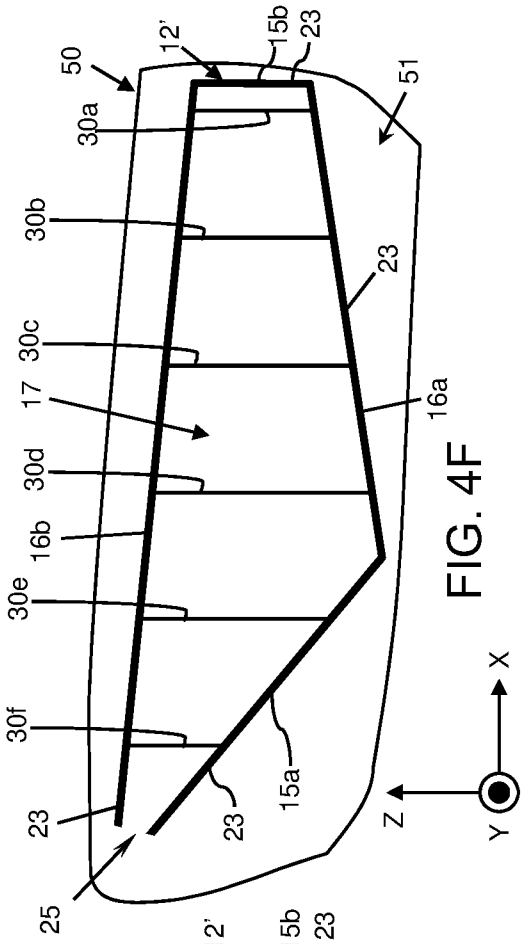


FIG. 4F

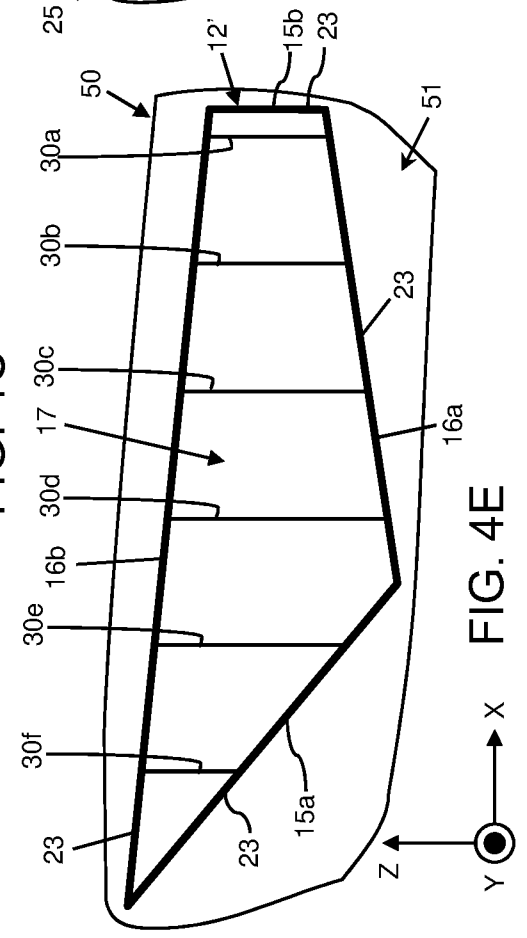


FIG. 4E

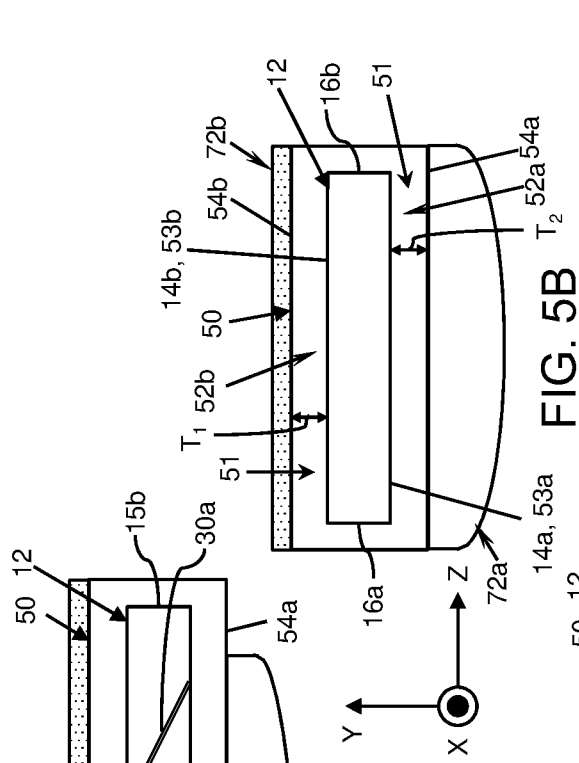


FIG. 5B

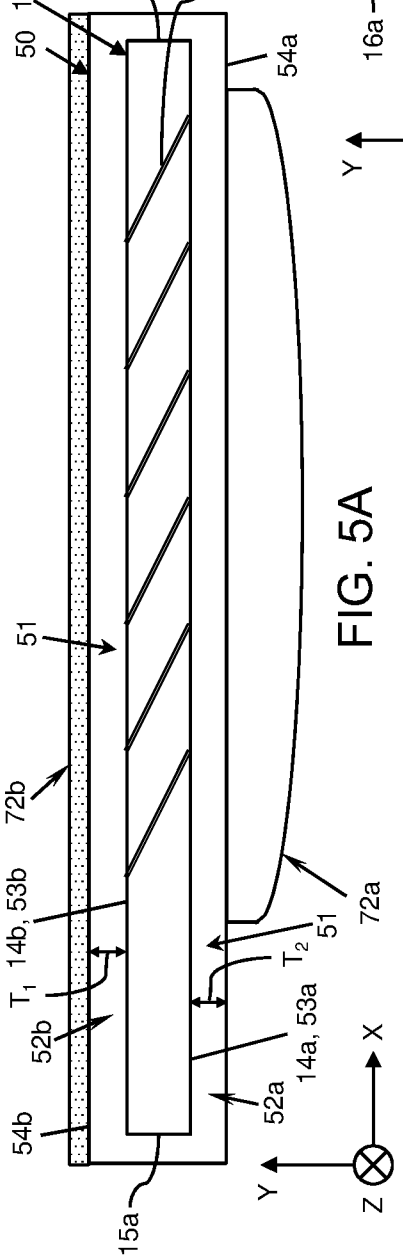


FIG. 5A

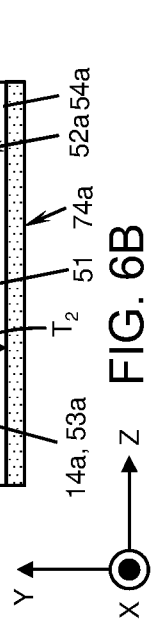


FIG. 6B

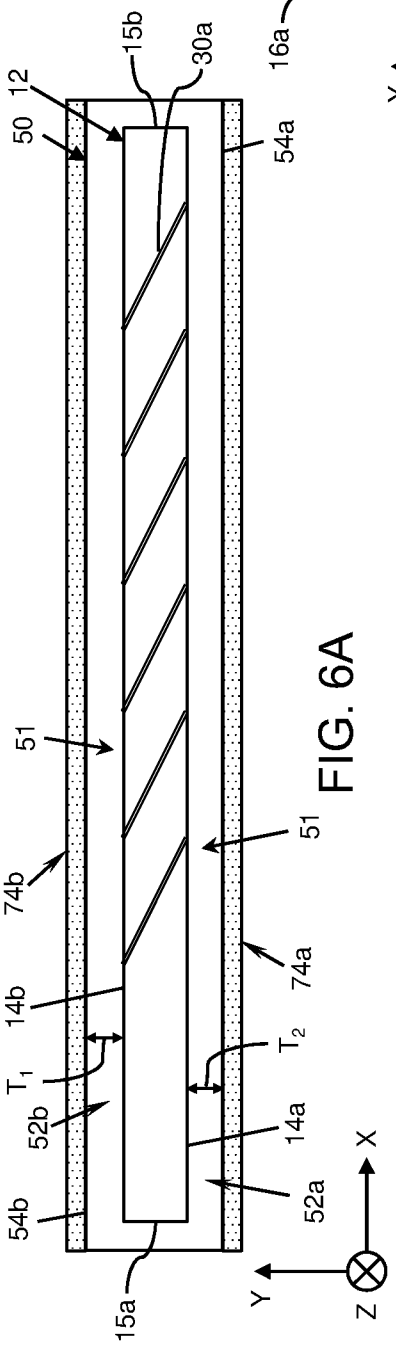


FIG. 6A

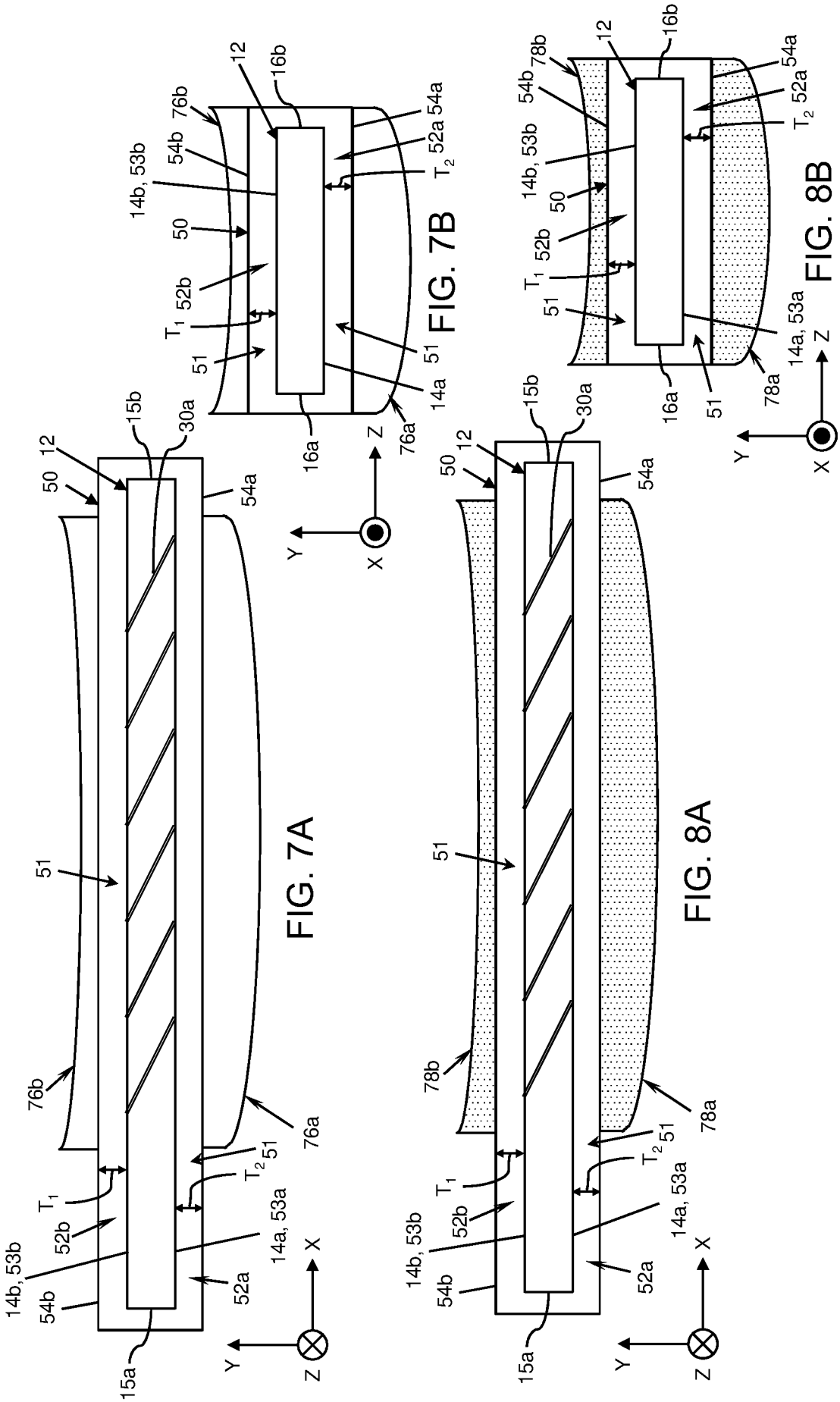


FIG. 7B

FIG. 8B

FIG. 7A

FIG. 8A

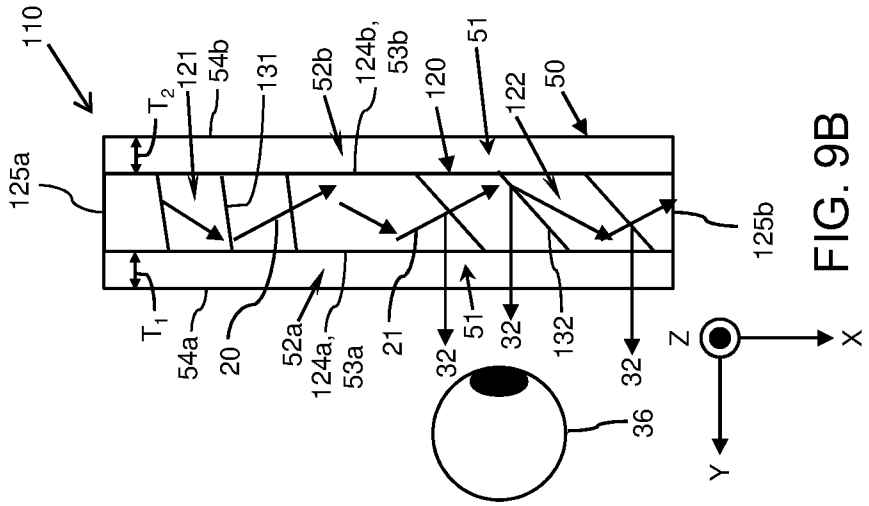

110
T_2
121
54b
131
52b
124b,
53b
120
51
122
50
125a
125b
T_1
54a
20
52a
124a,
53a
21
51
32
32
132
32
36
Z
X
Y

FIG. 9B

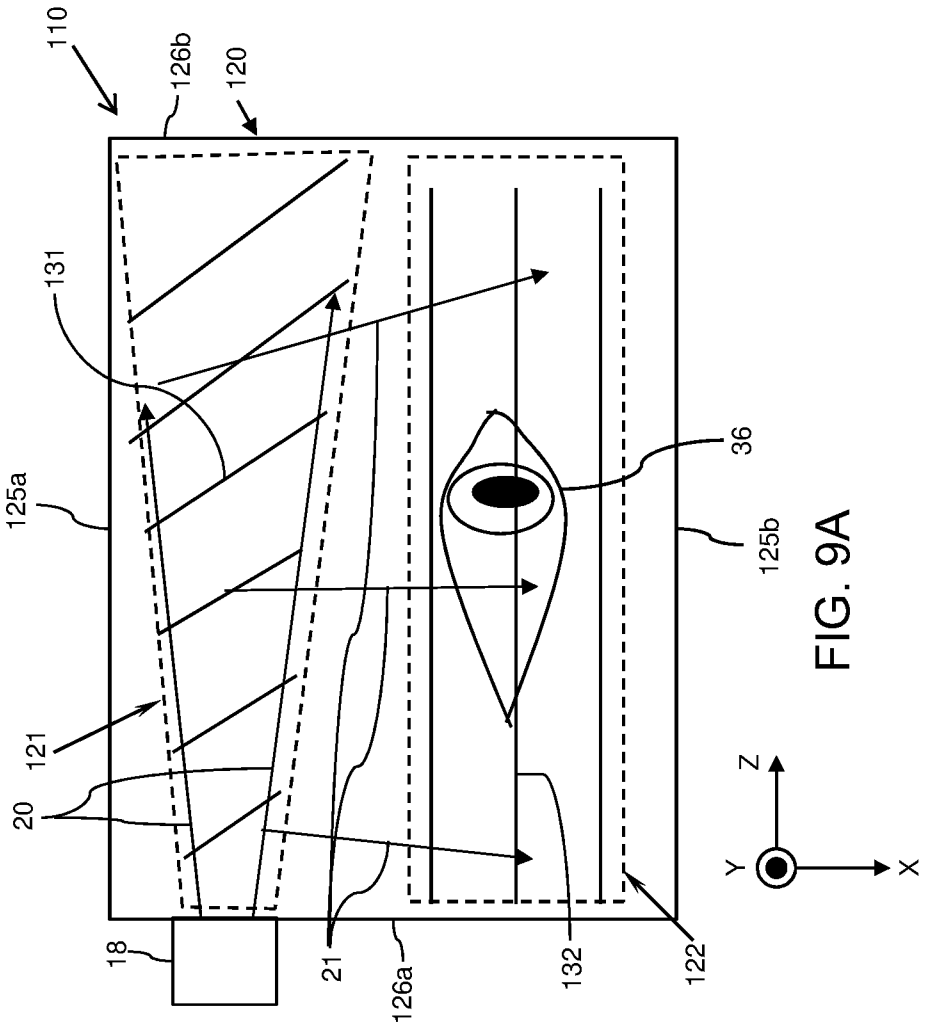

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126b
120
131
125a
36
125b
121
20
18
21
126a
132
122
Z
Y
X

FIG. 9A

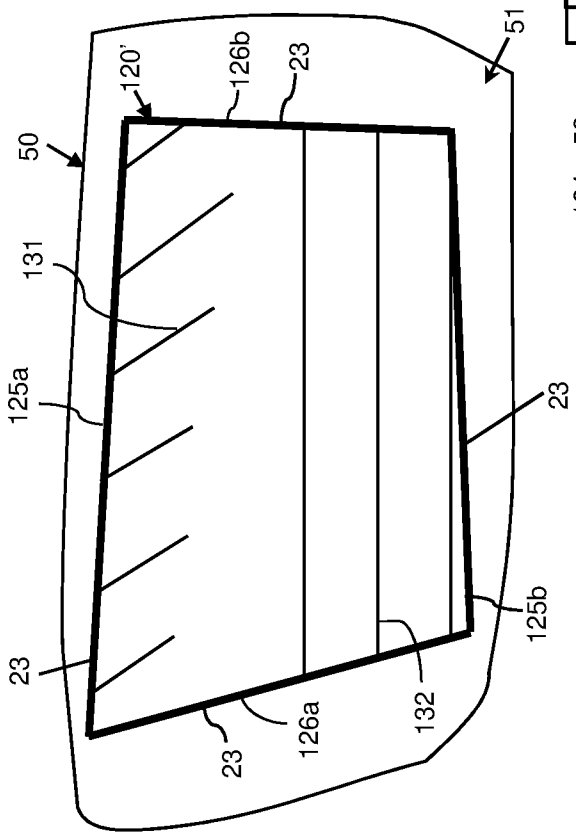


FIG. 10

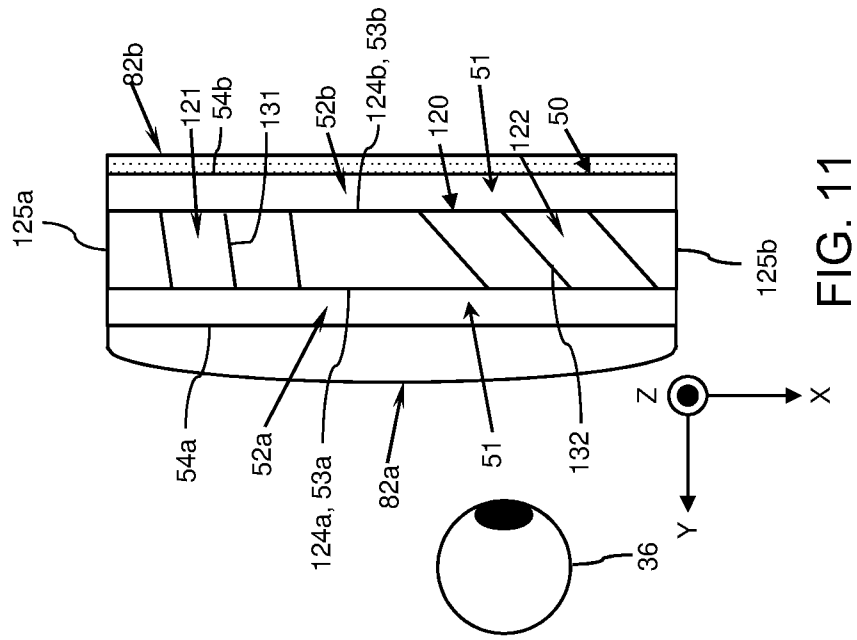


FIG. 11

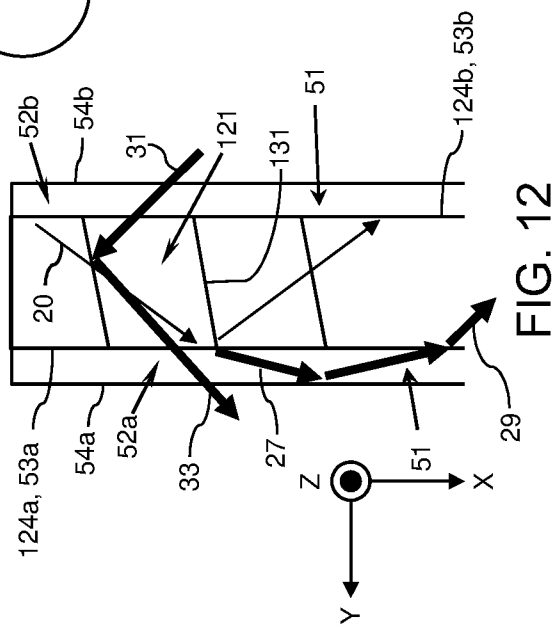


FIG. 12

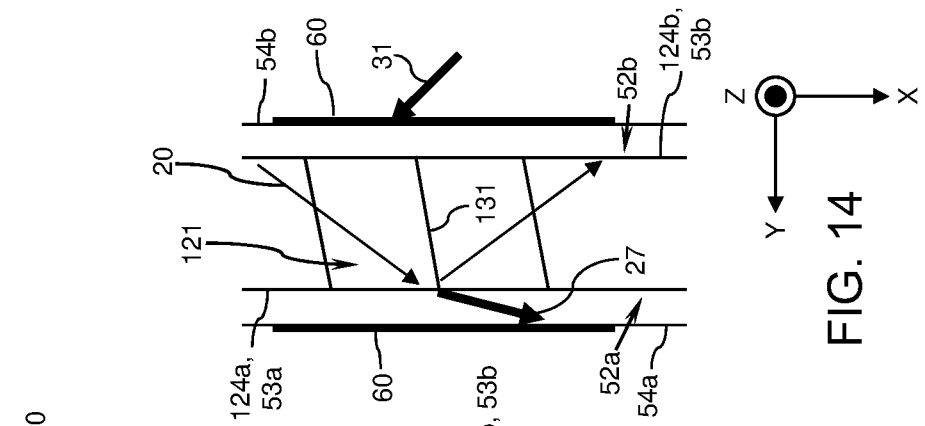


FIG. 14

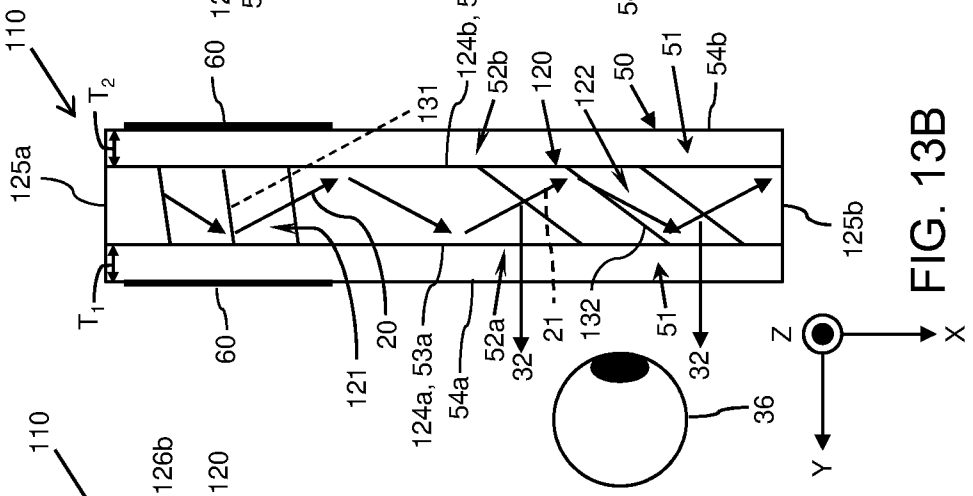


FIG. 13B

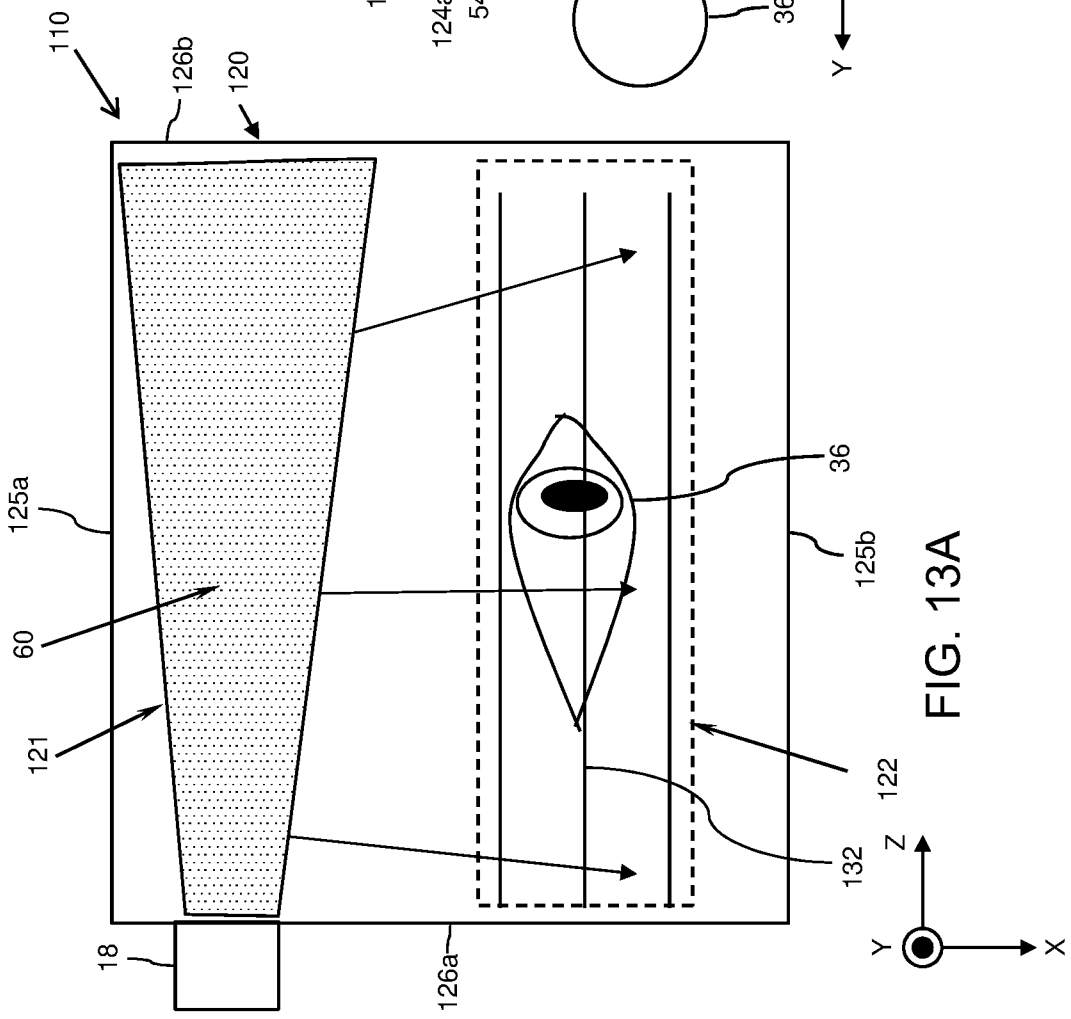


FIG. 13A

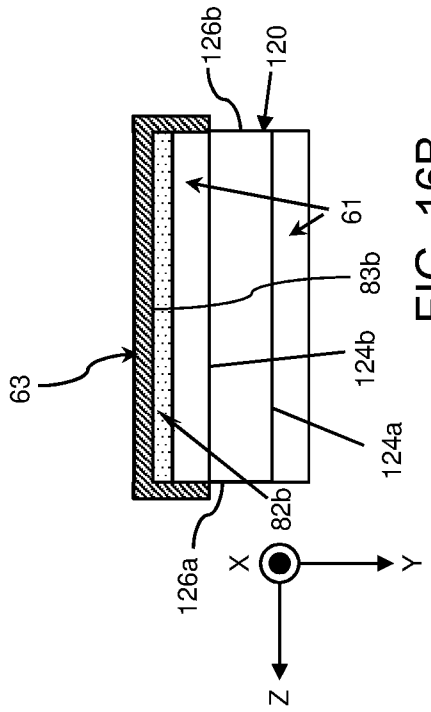


FIG. 16B

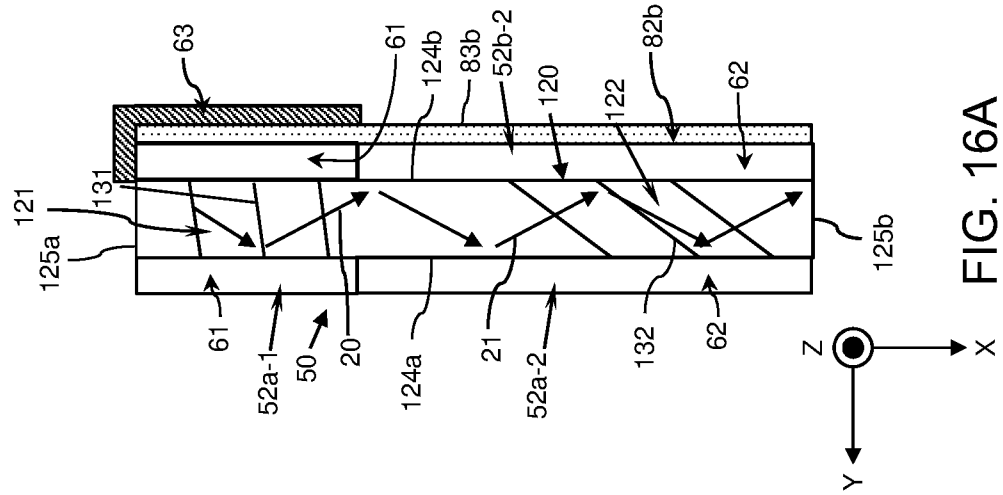


FIG. 16A

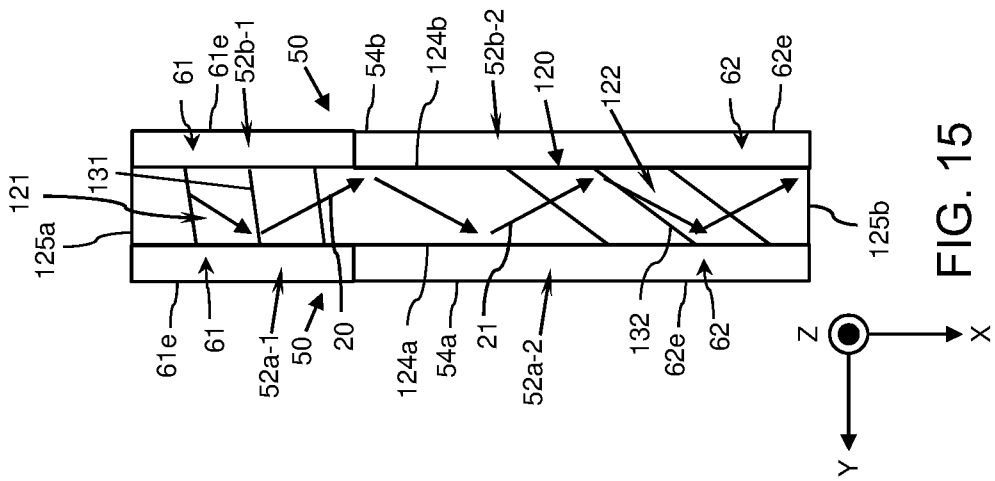


FIG. 15

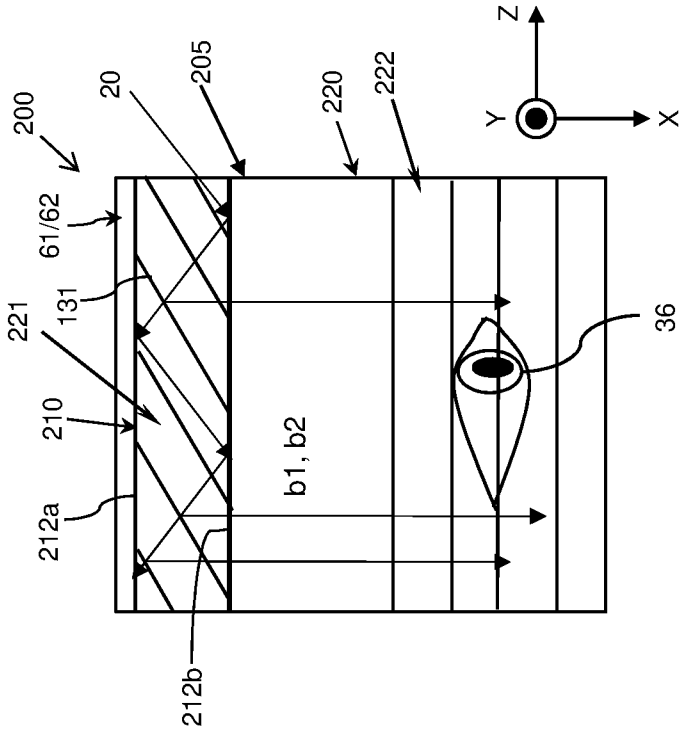


FIG. 17B

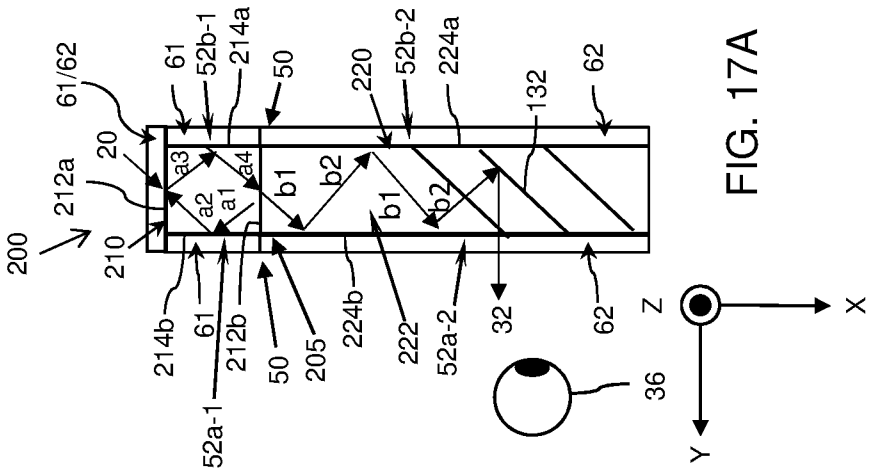


FIG. 17A

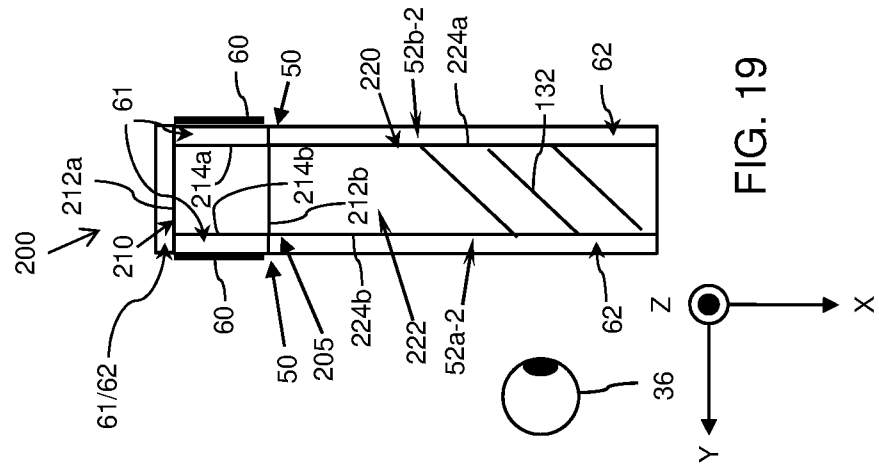

200
212a
210
61
60
50
220
52b-2
224a
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62
214a
214b
212b
61/62
205
224b
222
52a-2
36
Z
X
Y

FIG. 19

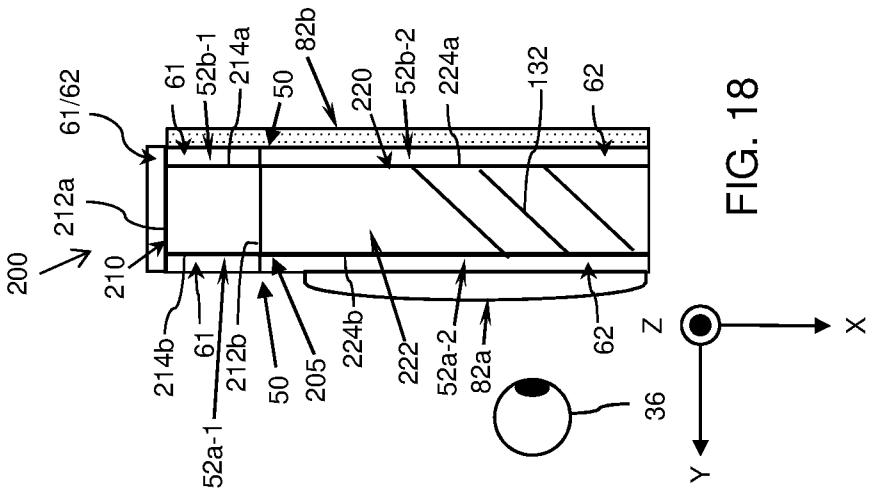

200
212a
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212b
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224b
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52a-2
82a
52a-1
36
Z
X
Y

FIG. 18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2022/050621

A. CLASSIFICATION OF SUBJECT MATTER

G02B 6/10(2022.01)i; ***G02B 27/09***(2022.01)i; ***G02B 27/01***(2022.01)i
CPC:G02B 6/10; G02B 27/095; G02B 2027/015; G02B 27/0172; G02B 2027/0178; G02B 2027/0125

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)

G02B 6/10; G02B 27/09; G02B 27/01
CPC:G02B 6/10; G02B 27/095; G02B 2027/015; G02B 27/0172; G02B 2027/0178; G02B 2027/0125

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: Orbit, Similari (AI-based)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013242392 A1 (AMIRPARVIZ BABAK ; WANG CHIA-JEAN; GOOGLE INC) 19 September 2013 (2013-09-19) The entire document	1,9,10,12-17, 22-27,31-35,37
X	US 2019278086 A1 (LUMUS LTD.) 12 September 2019 (2019-09-12) The entire document	1-4,6-8,11,18-20,22,28-30
Y		12,21
X	WO 2020044198 A1 (LUMUS LTD) 05 March 2020 (2020-03-05) The entire document	1,22
X	US 2021141225 A1 (ESSILOR INT.) 13 May 2021 (2021-05-13) The entire document	1,22
Y	US 2021033773 A1 (LUMUS LTD) 04 February 2021 (2021-02-04) The entire document	12,21

☑ 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
22 September 2022	**22 September 2022**

Name and mailing address of the ISA/IL
Israel Patent Office
Technology Park, Bldg.5, Malcha, Jerusalem, 9695101,
Israel
Israel
Telephone No. **972-73-3927203**
Email: **pctoffice@justice.gov.il**

Authorized officer
ABRAMOVICH Saar
Telephone No.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	WO 2021260708 A2 (LUMUS LTD) 30 December 2021 (2021-12-30) Fig. 6A ; p.4 ll.13-16 ; p.14 ll.9-15	1
A	WO 2021009766 A1 (LUMUS LTD) 21 January 2021 (2021-01-21) The entire document	1-4,6-35,37
A	US 2020183159 A1 (LUMUS LTD) 11 June 2020 (2020-06-11) The entire document	37

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2022/050621

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☑ Claims Nos.: **5,36**
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

[0001] The scope of protection sought is claim 5 not clear, since the feature of "sufficiently small such that surface patterns of the optical material follow blemish patterns at the major external surfaces" is ill-defined. Claim 36 recites that "at least one protective film associated at least with a portion of the at least one transparent material "and that "the at least one protective film is associated with a portion of at least one of the major external surfaces in the first region". Thus, the claim is not clear since the claim suggests that the same films are associated with both the transparent material and a major external surface in the first region, contrary to the formerly sought feature of "at least one transparent material directly attached to the LOE at least at the major external surfaces so as to be in direct contact with the major external surfaces and so as to at least partially encapsulate the LOE… so as to maintain conditions of total internal reflection at the major external surfaces".

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IL2022/050621

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
US 2013242392 A1	19 September 2013	US 2013242392 A1	19 September 2013
		US 8848289 B2	30 September 2014
		CN 104145208 A	12 November 2014
		CN 104145208 B	29 March 2017
		WO 2013138202 A1	19 September 2013
US 2019278086 A1	12 September 2019	US 2019278086 A1	12 September 2019
		US 10739598 B2	11 August 2020
		CN 109154720 A	04 January 2019
		EP 3458898 A1	27 March 2019
		EP 3458898 A4	11 March 2020
		IL 262566 A	31 December 2018
		IL 262566 B	30 November 2020
		JP 2019517018 A	20 June 2019
		JP 6740366 B2	12 August 2020
		KR 20190008311 A	23 January 2019
		TW 201805692 A	16 February 2018
		TW I712821 B	11 December 2020
		WO 2017199232 A1	23 November 2017
WO 2020044198 A1	05 March 2020	WO 2020044198 A1	05 March 2020
		AU 2019330119 A1	15 April 2021
		BR 112021003215 A2	11 May 2021
		CA 3109796 A1	05 March 2020
		CN 112601993 A	02 April 2021
		EP 3841414 A1	30 June 2021
		EP 3841414 A4	29 September 2021
		IL 280934 A	29 April 2021
		JP 2021535412 A	16 December 2021
		KR 20210047790 A	30 April 2021
		TW 202016595 A	01 May 2020
		US 2021271006 A1	02 September 2021
US 2021141225 A1	13 May 2021	US 2021141225 A1	13 May 2021
		US 11243398 B2	08 February 2022
		CN 110392860 A	29 October 2019
		CN 110392860 B	28 September 2021
		EP 3376279 A1	19 September 2018
		EP 3376279 B1	31 August 2022
		JP 2020512576 A	23 April 2020
		JP 7127049 B2	29 August 2022
		KR 20190126064 A	08 November 2019
		WO 2018166921 A1	20 September 2018
US 2021033773 A1	04 February 2021	US 2021033773 A1	04 February 2021
		US 11385393 B2	12 July 2022
		AU 2018403542 A1	30 January 2020
		BR 112020002041 A2	08 September 2020
		CA 3068946 A1	25 July 2019
		CN 111095060 A	01 May 2020
		CN 111095060 B	03 June 2022
		CN 114815261 A	29 July 2022
		CN 210005798 U	31 January 2020

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IL2022/050621

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
		DE 202019101599 U1	06 May 2019
		EP 3740795 A1	25 November 2020
		EP 3740795 A4	14 April 2021
		IL 276206 A	30 September 2020
		IL 276206 B	01 August 2022
		JP 3222983 U	12 September 2019
		JP 2021510838 A	30 April 2021
		KR 20190002425 U	30 September 2019
		KR 20200104849 A	04 September 2020
		RU 2020100274 A	21 February 2022
		RU 2020100274 A3	21 February 2022
		TW M598952 U	21 July 2020
		TW 201932894 A	16 August 2019
		US 2019227215 A1	25 July 2019
		US 10551544 B2	04 February 2020
		WO 2019142177 A1	25 July 2019
WO 2021260708 A2	30 December 2021	WO 2021260708 A2	30 December 2021
		WO 2021260708 A3	24 February 2022
		TW 202206892 A	16 February 2022
WO 2021009766 A1	21 January 2021	WO 2021009766 A1	21 January 2021
		WO 2021009766 A8	22 April 2021
		IL 289798 A	01 March 2022
		KR 20220035088 A	21 March 2022
		TW 202127071 A	16 July 2021
US 2020183159 A1	11 June 2020	US 2020183159 A1	11 June 2020
		AU 2017301074 A1	26 April 2018
		AU 2017301074 B2	03 February 2022
		AU 2017356702 A1	21 June 2018
		AU 2017356702 B2	15 April 2021
		AU 2022202969 A1	26 May 2022
		BR 112018006747 A2	16 October 2018
		BR 112018014673 A2	11 December 2018
		CA 2992213 A1	09 April 2018
		CA 3007002 A1	17 May 2018
		CN 108235739 A	29 June 2018
		CN 108235739 B	16 March 2021
		CN 108369317 A	03 August 2018
		CN 108369317 B	13 April 2021
		CN 109828376 A	31 May 2019
		CN 109828376 B	18 May 2021
		CN 113031165 A	25 June 2021
		CN 113156647 A	23 July 2021
		EP 3365712 A1	29 August 2018
		EP 3365712 A4	01 May 2019
		EP 3365712 B1	01 June 2022
		EP 3371635 A1	12 September 2018
		EP 3371635 A4	13 March 2019
		EP 3371635 B1	04 May 2022
		EP 3540484 A1	18 September 2019
		EP 3540484 B1	04 November 2020

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IL2022/050621

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
		EP	4036620	A1	03 August 2022
		IL	258941	A	31 May 2018
		IL	258941	B	29 November 2018
		IL	259957	A	31 October 2018
		IL	259957	B	29 July 2021
		IL	262558	A	31 December 2018
		IL	262558	B	30 November 2020
		JP	2020506409	A	27 February 2020
		JP	6829482	B2	10 February 2021
		JP	2019535024	A	05 December 2019
		JP	2021073498	A	13 May 2021
		KR	20190079581	A	05 July 2019
		KR	102310397	B1	08 October 2021
		KR	20190054081	A	21 May 2019
		KR	20190059870	A	31 May 2019
		KR	20210125098	A	15 October 2021
		MX	2018003097	A	01 August 2018
		MX	2018007164	A	06 June 2019
		RU	2746980	C1	22 April 2021
		RU	2018123182	A	26 December 2019
		RU	2018123182	A3	17 June 2021
		RU	2763850	C2	11 January 2022
		TW	201819970	A	01 June 2018
		TW	I653478	B	11 March 2019
		TW	201901207	A	01 January 2019
		TW	I684037	B	01 February 2020
		TW	202020494	A	01 June 2020
		TW	I703359	B	01 September 2020
		TW	202101050	A	01 January 2021
		US	2018210202	A1	26 July 2018
		US	10133070	B2	20 November 2018
		US	2018275384	A1	27 September 2018
		US	10437031	B2	08 October 2019
		US	2019064518	A1	28 February 2019
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		US	2020033572	A1	30 January 2020
		US	11378791	B2	05 July 2022
		WO	2018065975	A1	12 April 2018
		WO	2018087756	A1	17 May 2018