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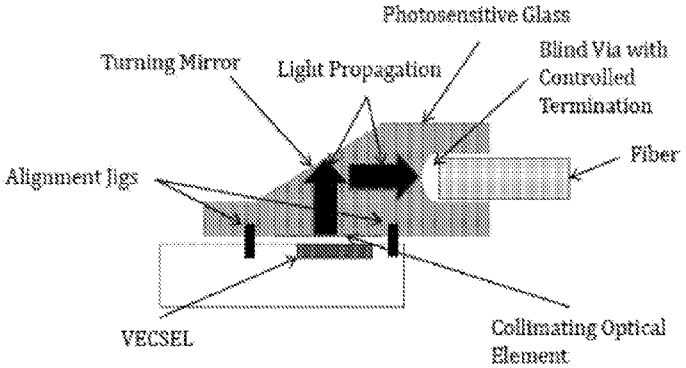


FIGURE 1

(57) Abstract: The present invention provides a method to fabricate an optical coupler comprising the steps of: preparing a photosensitive glass substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide; masking a halftone design with variation in optical density to delineate an optical element in the glass; exposing the photosensitive glass substrate to an activating energy source; exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature; cooling the photosensitive glass substrate to transform at least part of the exposed glass to a crystalline material to form a glass-crystalline substrate; and etching the glass-crystalline substrate with an etchant solution to form the one or more optical elements.

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METHODS OF FABRICATING PHOTOSENSITIVE SUBSTRATES SUITABLE FOR OPTICAL COUPLER

Field of Invention

The present invention relates to a method to fabricate a glass structure and, in particular, a method for a monolithic optical coupler for directing light from a laser diode to an optical fiber glass-ceramic substrate for focusing, collimating, and imaging in general..

Background Art

Photosensitive glass structures have been suggested for a number of micromachining and microfabrication processes such as integrated imaging elements in conjunction with other elements systems or subsystems, micro-lens, micro-lens arrays. Silicon microfabrication of traditional glass is expensive and low yield while injection molding or embossing processes produce inconsistent optical shapes and micro lenses. Silicon microfabrication processes rely on expensive capital equipment; photolithography and reactive ion etching tools that generally cost in excess of one million dollars each and require an ultra-clean, high-production silicon fabrication facility costing millions to billions more. Injection molding and embossing are less costly methods of producing a micro-lens but generate defects within the transfer or have differences due to the stochastic curing process.

This invention creates a cost effective glass ceramic optical coupling device based integrated lens, mirrors and waveguide elements. Where glass ceramic substrate has demonstrated capability to form such structures through the processing of both the vertical as well as horizontal planes either separately or at the same time to form three optical coupling devices or an array of devices.

Summary of the Invention

The present invention includes a method to fabricate a substrate with one or more optical micro-lens by preparing a photosensitive glass substrate and further coating with one or more metals.

The present invention provides a method to fabricate an optical coupler comprising the steps of: preparing a photosensitive glass substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide; masking a halftone design with variation in optical density to delineate an optical element in the glass; exposing the photosensitive glass substrate to an activating energy source; exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature; cooling the photosensitive glass substrate to transform at least part of the exposed glass to a crystalline material to form a glass-crystalline substrate; and etching the glass-crystalline substrate with an etchant solution to form the one or more optical elements.

The present invention provides a method to fabricate an optical element comprising the steps of: preparing a photosensitive glass substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide; masking a digital mask consists of transparent and non-transparent elements to define a diffractive optical element in the glass; exposing at least one portion of the photosensitive glass substrate to an activating energy source; exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature; cooling the photosensitive glass substrate to transform at least part of the exposed glass to a crystalline material to form a glass-crystalline substrate; and etching the glass-crystalline substrate with an etchant solution to form the one or more micro-lens device(s).

The one or more optical elements may be one or more micro-lens. The photosensitive glass substrate may be 60 - 76 weight % silica; at least 3 weight % K_2O with 6 weight % - 16 weight % of a combination of K_2O and Na_2O; 0.003 - 1 weight % of at least one oxide selected from the group consisting of Ag_2O and Au_2O; 0.003 - 2 weight % Cu_2O; 0.75 weight % - 7 weight % B_2O_3, and 6 - 7 weight % Al_2O_3; with the combination of B_2O_3 and Al_2O_3 not exceeding 13 weight %; 8-15 weight % Li_2O; and 0.001 – 0.1 weight % CeO_2. The optical element may be circular with a high optical density on the perimeter and low optical density in the center. The optical element may be a micro-lens comprising a high optical density on the perimeter and a low optical density in the center. The one or more optical elements provide the optical power. The halftone design provides the optical power of the optical element. The optical element may be a pattern of high optical density with concentric circles. The optical element may be a diffractive pattern of concentric circles. The optical element forms a diffractive optical micro-lens. The pattern of concentric circular circles provide the optical power of the optical element.

A method of fabrication and device made by preparing a photosensitive glass ceramic composite substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide, masking a design layout comprising one or more micro-lens on the photosensitive glass substrate, exposing at least one portion of the photosensitive glass substrate to an activating energy source, exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature, cooling the photosensitive glass substrate to transform at least part of the exposed glass to a crystalline material to form a glass-crystalline substrate and etching the glass-crystalline substrate with an etchant solution to form one or more angled channels, lens diffractive optical element waveguide and/or precision fiber guide.

Brief Description of the Drawings

Further benefits and advantages of the present invention will become more apparent from the following description of various embodiments that are given by way of example with reference to the accompanying drawings:

FIGURE 1 is an image of the optical coupler of the present invention.

FIGURE 2 is an image of a monolithic optical coupler of the present invention.

FIGURE 3 is an image of the angled etched features of the present invention; the angles can be at any angle from 0-45 degrees.

Description of the Invention

While the making and using of various embodiments of the present invention are discussed in detail below, it should be appreciated that the present invention provides many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments discussed herein are merely illustrative of specific ways to make and use the invention and do not delimit the scope of the invention.

To facilitate the understanding of this invention, a number of terms are defined below. Terms defined herein have meanings as commonly understood by a person of ordinary skill in the areas relevant to the present invention. Terms such as "a", "an" and "the" are not intended to refer to only a singular entity, but include the general class of which a specific example may be used for illustration. The terminology herein is used to describe specific embodiments of the invention, but their usage does not delimit the invention, except as outlined in the claims.

To address these needs, the present inventors developed a photosensitive glass ceramic (APEX® Glass ceramic) as a novel packaging and substrate material for semiconductors, RF electronics, microwave electronics, and optical imaging. APEX Glass ceramic is processed using first generation semiconductor equipment in a simple three step process and the final material can be fashioned into either glass, ceramic, or contain regions of both glass and ceramic. The APEX Glass ceramic possesses several benefits over current materials, including: easily fabricated high density vias, demonstrated microfluidic capability, micro-lens or micro-lens array, high Young's modulus for stiffer packages, halogen-free manufacturing, and economical manufacturing. Photosensitive glasses have several advantages for the fabrication of a wide variety of microsystems components. Microstructures have been produced relatively inexpensively with these glasses using conventional semiconductor processing equipment. In general, glasses have high temperature stability, good mechanical and electrical properties, and have better chemical resistance than plastics and many metals. To our knowledge, the only commercially available photosensitive glass is FOTURAN®, made by Schott Corporation and imported into the U.S.

only by Invenios Inc. FOTURAN® comprises a lithium-aluminum-silicate glass containing traces of silver ions. When exposed to UV-light, within the absorption band of cerium oxide, the cerium oxide acts as sensitizers, absorbing a photon and losing an electron that reduces neighboring silver oxide to form silver atoms, e.g.,

$$Ce^{3+} + Ag^{+} = \square Ce^{4+} + Ag^{0}$$

The silver atoms coalesce into silver nanoclusters during the baking process and induces nucleation sites for crystallization of the surrounding glass. If exposed to UV light through a mask, only the exposed regions of the glass will crystallize during subsequent heat treatment.

This heat treatment must be performed at a temperature near the glass transformation temperature (e.g., greater than 465°C. in air for FOTURAN®). The crystalline phase is more soluble in etchants, such as hydrofluoric acid (HF), than the unexposed vitreous, amorphous regions. In particular, the crystalline regions of FOTURAN® are etched about 20 times faster than the amorphous regions in 10% HF, enabling microstructures with wall slopes ratios of about 20:1 when the exposed regions are removed. See T. R. Dietrich et al., "Fabrication technologies for microsystems utilizing photosensitive glass," Microelectronic Engineering 30, 497 (1996), which is incorporated herein by reference.

Preferably, the shaped glass structure contains at least one of a micro-optic lens, a micro-optic element. The micro-optic lens is formed in one of three manners. First, the micro-optic lens can be fabricated by making a series of concentric circles to form a Fresnel lens. The index of refraction mismatch between the etched regions and the un-etched region of the concentric circles creates a diffractive optical element or Fresnel lens. Secondly, a Fresnel lens can be created by using a series of rings from a material that is deposited on the surface of the APEX Glass. As long as the concentric circles of the Fresnel lens have an index of refraction difference or a thickness difference, the Fresnel lens will apply the optical function to the incident electromagnetic radiation. The third approach is to etch a curved pattern or a step approximation of curved pattern. The curved or step approximation of curved pattern creates a lens where the power of the lens is given by the slope of the curvature and the specific optical function given by the overall shape of the structure.

FOTURAN® is described in information supplied by Invenios (the sole source U.S. supplier for FOTURAN®) and is composed of silicon oxide (SiO_2) of 75-85% by weight, lithium oxide (Li_2O) of 7-11% by weight, aluminum oxide (Al_2O_3) of 3-6% by weight, sodium oxide (Na_2O) of 1-2% by weight, 0.2-0.5% by weight antimonium trioxide (Sb_2O_3) or arsenic oxide (As_2O_3), silver oxide (Ag_2O) of 0.05-0.15% by weight, and cerium oxide (CeO_2) of 0.01- 0.04% by

weight. As used herein, the terms "APEX Glass ceramic", "APEX glass" or simply "APEX" is used to denote one embodiment of the glass ceramic composition of the present invention.

The present invention provides a single material approach for the fabrication of optical microstructures with photosensitive/photo-patternable APEX Glass for use in imaging applications by the shaped APEX Glass structures that are used for lenses and includes through-layer or in-layer designs.

Generally, glass ceramics materials have had limited success in microstructure formation plagued by performance, uniformity, usability by others and availability issues. Past glass-ceramic materials have a yield etch aspect-ratio of approximately 15:1. In contrast, APEX Glass has an average etch aspect-ratio greater than 50:1. This allows users to create smaller and deeper features. Additionally, our manufacturing process enables product yields of greater than 90% (legacy glass yields are closer to 50%). Lastly, in legacy glass ceramics, approximately 30% of the glass is converted into the ceramic state, whereas with APEX Glass ceramic this conversion is closer to 70%.

The present invention includes a method for fabricating a glass ceramic structure for use in forming angled structures, mirrors and glass ceramic materials used in electromagnetic transmission and filtering applications. The present invention includes an angled structure created in the multiple planes of a glass ceramic substrate, such process employing the (a) exposure to excitation energy such that the exposure occurs at various angles by either altering the orientation of the substrate or of the energy source, (b) a bake step and (c) an etch step. Angle sizes can be either acute or obtuse. The curved and digital structures are difficult, if not infeasible to create in most glass, ceramic or silicon substrates. The present invention has created the capability to create such structures in both the vertical as well as horizontal plane for glass ceramic substrates. The present invention includes a method for fabricating glass ceramic micro-lens structures for use in imaging. The lens structure can be coated with various metals or oxides, thin films or other materials to modify the index of refraction (e.g., mirrors) or transparent materials to create a lens. In optics, the refractive index (or index of refraction) of a substance (optical medium) is a number that describes how light, or any other radiation, propagates through that medium.

The present invention allows for the development of negative refractive index structures, which can occur if permittivity and permeability have simultaneous negative values. The resulting negative refraction offers the possibility of creating lenses and other exotic optical structures.

Ceramicization of the glass is accomplished by exposing the entire glass substrate to approximately 20J/cm^2 of 310nm light. When trying to create glass spaces within the ceramic,

users expose all of the material, except where the glass is to remain glass. In one embodiment, the present invention provides a quartz-chrome mask containing a variety of concentric circles with different diameters.

The present invention includes a method for fabricating a glass ceramic structure for use in forming imaging structures, diffractive optical element, mirrors and micro-lens, micro-lens array in glass ceramic materials used in electromagnetic transmission and reflecting applications. The glass ceramic substrate may be a photosensitive glass substrate having a wide number of compositional variations including but not limited to: 60 - 76 weight % silica; at least 3 weight % K_2O with 6 weight % - 16 weight % of a combination of K_2O and Na_2O; 0.003-1 weight % of at least one oxide selected from the group consisting of Ag_2O and Au_2O; 0.003-2 weight % Cu_2O; 0.75 weight % - 7 weight % B_2O_3, and 6 - 7 weight % Al_2O_3; with the combination of B_2O_3; and $A_{l2}O_3$ not exceeding 13 weight %; 8-15 weight % Li_2O; and 0.001 – 0.1 weight % CeO_2. This and other varied compositions are generally referred to as the APEX Glass.

The exposed portion may be transformed into a crystalline material by heating the glass substrate to a temperature near the glass transformation temperature. When etching the glass substrate in an etchant such as hydrofluoric acid, the anisotropic-etch ratio of the exposed portion to the unexposed portion is at least 30:1 when the glass is exposed to a broad spectrum mid-ultraviolet (about 308-312 nm) flood lamp to provide a shaped glass structure that has an aspect ratio of at least 30:1, and to provide a lens shaped glass structure. The mask for the exposure can be of a halftone mask that provides a continuous grey scale to the exposure to form a curved structure for the micro-lens. A digital mask used with the flood exposure can be used to produce a diffractive optical element or Fresnel lens. The exposed glass is then typically baked in a two-step process. Temperature range heated between of 420°C-520°C for between 10 minutes to 2 hours, for the coalescing of silver ions into silver nanoparticles and temperature range heated between 520°C-620°C for between 10 minutes and 2 hours allowing the lithium oxide to form around the silver nanoparticles. The glass substrate is then etched. The glass substrate is etched in an etchant, of HF solution, typically 5% to 10% by volume, wherein the etch-ratio of exposed portion to that of the unexposed portion is at least 30:1 when exposed with a broad spectrum mid-ultraviolet flood light, and greater than 30:1 when exposed with a laser, to provide a shaped glass structure with an anisotropic etch ratio of at least 30:1.

The optical coupler is the combination of a fiber alignment guide, tuning mirror, collimating optical element (such as a lens or diffractive optical element) and coupling optical element (such as a lens or diffractive optical element). These optical elements exist as discrete devices that are assembled by hand with low yield and poor performance. This invention offers the first

monolithic structure created on a single photosensitive glass substrate without subsequent assembly. The monolithic optical coupler has an alignment jig for the VECSEL to be inserted or for external alignment jigs to mate up. On the inside of the jig is an optical element that collimates the emission from the VECSEL. The collimating optical element can be either a curved lens formed from etching or a series of etched grooves that create a diffractive lens. The collimated light travels to a turning mirror to reflect the light 90°. The reflected light is transmitted through the glass and pass through the controlled termination of the blind via. The controlled termination is a curved termination. The curved termination acts as a lens that images the light into the fiber that is held in the etched blind via. The cylindrical via is at least 5% greater in diameter than of the fiber. See Figure 1.

A second version of the monolithic optical coupler has an alignment jig for the VECSEL to be inserted or for external alignment jigs to mate up. On the inside of the jig is an optical element in the photosensitive glass that collimates the emission from the VECSEL. The collimating optical element can be either a curved lens formed from etching or a series of etched grooves that create a diffractive lens. The collimated light form the VECSEL is transmitted the photosensitive glass where it passes through the controlled termination of the blind via. The controlled termination is a curved termination. The curved termination acts as a lens that images the light into the fiber that is held in the etched blind via. The cylindrical via is at least 5% greater in diameter than of the fiber. See Figure 2.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed, that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

General Photoactive Glass Manufacturing Design Rules: Boron Oxide and Aluminum oxide basically conduct the same task within the glass melt. Boron oxide may also be in the form of anhydride boric acid (H_3BO_3), Borax Frits, Gerstley Borate/Colemanite, Boric Acid, Borax, and

Ulexite. A 13 weight percent represents the high end of B_2O_3 in borosilicate glasses. Boron Oxide concentration range: Up to 13 weight percent. Aluminum oxide may be in the form of Alkali containing feldspars (such as Albite, $NaAlSi_3O_8$) or alumina hydrate. Al_2O_3 may be added by using kaolin or nepheline syenite (which contains feldspar). Up to 8 weight percent. This represents the high end of Al_2O_3 in borosilicate glasses crystallization Aluminum Oxide concentration range: up to 7 weight percent. Or more appropriately, the combination of Boron Oxide and Aluminum Oxide should not exceed 13 weight percent.

Potassium Oxide and Sodium Oxide basically conduct the same task within the glass melt. Potassium oxide: Helps lower melting point. Sometimes used to replace sodium in soda lime glasses. Range up to 16 weight percent as well. May also be Potash (K_2CO_3). If used to replace Na_2O, typically makes the glass more chemically resistant.

Potassium Oxide concentration range: up to 16 weight percent. Sodium oxide helps lower melting point. Range up to 16 weight percent (common high end for soda lime glass). May also be soda ash (Na_2CO_3) or Glauber's Salt (Na_2SO_4). Sodium oxide concentration range: up to 16 weight percent. Or more appropriately, the combination of these two should not exceed 16 weight percent. Silica: concentration range: 60-85 weight percent.

Zinc oxide: Improves chemical resistance, lowers thermal expansion, adds elasticity. Works similarly with CaO. Up to 18 weight percent in E-Glass. Zinc Oxide concentration range: up to 18 weight percent. Lithium Oxide: Aids in nucleation. Can be lithium carbonate. Lithium Oxide concentration range: 8-15 weight percent.

Cerium Oxide: Electron Donor. Cerium oxide concentration range: up to 0.1 weight percent. Antimonium trioxide: Oxygen donor. Antimonium trioxide (Sb_2O_3) concentration range: up to 0.5 weight percent. Arsenic Oxide: Oxygen donor. Arsenic oxide (As_2O_3): Electron Donor. Arsenic Oxide concentration range: up to 0.1 weight.

Silver Oxide concentration range: up to 1 weight percent. Gold Oxide concentration range: up to 1 weight percent. Copper Oxide concentration range: up to 2 weight percent.

The above ingredients might be at least partially replaced with the following compounds: Calcium Oxide: Improves chemical resistance, lowers thermal expansion, adds elasticity. Works similarly with ZnO. Up to 18 weight percent in E-Glass. Calcium Oxide concentration range: up to 18 weight percent. Magnesium Oxide: This is the upper end in E-glass. May be in the form of $MgCO_3$. Magnesium oxide concentrate range: up to 10 weight percent. Barium Oxide: Improves refractive index of the material without increasing the dispersive power. Used as a replacement for lead or lime. May also come in the form of $BaCO_3$. Barium Oxide concentration range: up to 18 weight percent. Lead Oxide: Improves refractive index of the

material without increasing the dispersive power. Lead Oxide concentration range: up to 18 weight percent.

Iron may be added to the melt to make the material paramagnetic (e.g. Fe_2O_3). Iron oxide may additionally be used to quench intrinsic autofluorescence of other compounds within the glass. Iron Oxide Concentration range: up to 5 weight percent.

Processing parameters. Patterning of the selected area(s) by at least one process step selected from the group consisting of: Exposure–Exposing the glass substrate to an activating energy source, such as 310nm light or a directed source of protons.

High anisotropic-etch ratios may be obtained using the photoactive glass of the present invention using a total activation energy between 0.01 J/cm^2 and 10 J/cm^2 of 310nm light. In contrast, FOTURAN® sometimes requires up to 85 J/cm^2 activation energy to create a uniform exposure across large distances (i.e., inches).

Baking—Baking typically occurs in a two step process. Temperature 1 allows for the coalescing of silver ions into silver nanoparticles and temperature 2 allows for the lithium oxide to form around the silver nanoparticles. However, we have been successful in doing a single ramp step.
Etching—Etching is done in an HF solution, typically 5-10 percent by volume. However, we can also add other fluids to the etch solution. For example, we can add hydrochloric or nitric acid to the etch solution. We've had good success in using this solution to obtain a smoother etch because it dissolves the silver nanoparticles. This etch is especially useful in the fabrication of structures and devices that require a smooth surfaces, such as micro-lenses.

It will be understood that particular embodiments described herein are shown by way of illustration and not as limitations of the invention. The principal features of this invention can be employed in various embodiments without departing from the scope of the invention. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, numerous equivalents to the specific procedures described herein. Such equivalents are considered to be within the scope of this invention and are covered by the claims.

The use of the word "a" or "an" when used in conjunction with the term "comprising" in the claims and/or the specification may mean "one," but it is also consistent with the meaning of "one or more," "at least one," and "one or more than one." The use of the term "or" in the claims is used to mean "and/or" unless explicitly indicated to refer to alternatives only or the alternatives are mutually exclusive, although the disclosure supports a definition that refers to only alternatives and "and/or." Throughout this application, the term "about" is used to indicate

that a value includes the inherent variation of error for the device, the method being employed to determine the value, or the variation that exists among the study subjects.

As used in this specification and claim(s), the words "comprising" (and any form of comprising, such as "comprise" and "comprises"), "having" (and any form of having, such as "have" and "has"), "including" (and any form of including, such as "includes" and "include") or "containing" (and any form of containing, such as "contains" and "contain") are inclusive or open-ended and do not exclude additional, un-recited elements or method steps. In embodiments of any of the compositions and methods provided herein, "comprising" may be replaced with "consisting essentially of" or "consisting of". As used herein, the phrase "consisting essentially of" requires the specified integer(s) or steps as well as those that do not materially affect the character or function of the claimed invention. As used herein, the term "consisting" is used to indicate the presence of the recited integer (e.g., a feature, an element, a characteristic, a property, a method/process step or a limitation) or group of integers (e.g., feature(s), element(s), characteristic(s), properties(s), method/process steps or limitation(s)) only.

As used herein, words of approximation such as, without limitation, "about", "substantial" or "substantially" refers to a condition that when so modified is understood to not necessarily be absolute or perfect but would be considered close enough to those of ordinary skill in the art to warrant designating the condition as being present. The extent to which the description may vary will depend on how great a change can be instituted and still have one of ordinary skilled in the art recognize the modified feature as still having the required characteristics and capabilities of the unmodified feature. In general, but subject to the preceding discussion, a numerical value herein that is modified by a word of approximation such as "about" may vary from the stated value by at least ±1, 2, 3, 4, 5, 6, 7, 10, 12 or 15%.

Additionally, the section headings herein are provided for consistency with the suggestions under 37 CFR 1.77 or otherwise to provide organizational cues. These headings shall not limit or characterize the invention(s) set out in any claims that may issue from this disclosure. Specifically, and by way of example, although the headings refer to a "Field of Invention," such claims should not be limited by the language under this heading to describe the so-called technical field. Further, a description of technology in the "Background of the Invention" section is not to be construed as an admission that technology is prior art to any invention(s) in this disclosure. Neither is the "Summary" to be considered a characterization of the invention(s) set forth in issued claims. Furthermore, any reference in this disclosure to "invention" in the singular should not be used to argue that there is only a single point of novelty in this disclosure.

Multiple inventions may be set forth according to the limitations of the multiple claims issuing from this disclosure, and such claims accordingly define the invention(s), and their equivalents, that are protected thereby. In all instances, the scope of such claims shall be considered on their own merits in light of this disclosure, but should not be constrained by the headings set forth herein.

All of the compositions and/or methods disclosed and claimed herein can be made and executed without undue experimentation in light of the present disclosure. While the compositions and methods of this invention have been described in terms of preferred embodiments, it will be apparent to those of skill in the art that variations may be applied to the compositions and/or methods and in the steps or in the sequence of steps of the method described herein without departing from the concept, spirit and scope of the invention. All such similar substitutes and modifications apparent to those skilled in the art are deemed to be within the spirit, scope and concept of the invention as defined by the appended claims.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification, but only by the claims.

CLAIMS

1. A method to fabricate an optical coupler comprising the steps of:

preparing a photosensitive glass substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide;

masking a halftone design with variation in optical density to delineate an optical element in the glass;

exposing the photosensitive glass substrate to an activating energy source;

exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature;

cooling the photosensitive glass substrate to transform at least part of the exposed glass to a crystalline material to form a glass-crystalline substrate; and

etching the glass-crystalline substrate with an etchant solution to form the one or more optical elements.

2. A method to fabricate an optical element comprising the steps of:

preparing a photosensitive glass substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide;

masking a digital mask consists of transparent and non-transparent elements to define a diffractive optical element in the glass;

exposing at least one portion of the photosensitive glass substrate to an activating energy source;

exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature;

cooling the photosensitive glass substrate to transform at least part of the exposed glass to a crystalline material to form a glass-crystalline substrate; and

etching the glass-crystalline substrate with an etchant solution to form the one or more micro-lens device(s).

3. The method of claims 1 or 2 wherein one or more optical elements comprise one or more micro-lens.

4. The method of any of claims 1 to 3 wherein the photosensitive glass substrate comprises 60 - 76 weight % silica; at least 3 weight % K_2O with 6 weight % - 16 weight % of a combination of K_2O and Na_2O; 0.003 - 1 weight % of at least one oxide selected from the group

consisting of Ag_2O and Au_2O; 0.003 - 2 weight % Cu_2O; 0.75 weight % - 7 weight % B_2O_3, and 6 - 7 weight % Al_2O_3; with the combination of B_2O_3 and $A_{l2}O_3$ not exceeding 13 weight %; 8-15 weight % Li_2O; and 0.001 – 0.1 weight % CeO_2.

5. The method of any of claims 1 to 4 wherein the optical element is circular with a high optical density on the perimeter and low optical density in the center.

6. The method of any of claims 1 to 5 wherein the optical element is a micro-lens comprising a high optical density on the perimeter and a low optical density in the center.

7. The method of any of claims 1 to 6 wherein the one or more optical elements provide the optical power.

8. The method of any of claims 1 to 7 wherein the halftone design provides the optical power of the optical element.

9. The method of any of claims 1 to 8 wherein the optical element comprises a pattern of high optical density with concentric circles.

10. The method of any of claims 1 to 9 wherein the optical element comprises a diffractive pattern of concentric circles.

11. The method of any of claims 1 to 10 wherein the optical element forms a diffractive optical micro-lens.

12. The method of any of claims 1 to 11 wherein the pattern of concentric circular circles provide the optical power of the optical element.

AMENDED CLAIMS
received by the International Bureau on 02 August 2017 (02.08.2017)

CLAIMS

1. A method to fabricate an optical coupler comprising the steps of:

preparing a photosensitive glass substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide;

masking a halftone design with variation in optical density to delineate an optical element in the glass;

exposing the photosensitive glass substrate to an activating energy source;

exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature;

cooling the photosensitive glass substrate to transform at least a portion of the exposed photosensitive glass substrate to a crystalline material to form a glass-crystalline substrate; and

etching the glass-crystalline substrate with an etchant solution to form the one or more optical elements.

2. A method to fabricate an optical element comprising the steps of:

preparing a photosensitive glass substrate comprising at least silica, lithium oxide, aluminum oxide, and cerium oxide;

masking a digital mask consisting of transparent and non-transparent elements to define a diffractive optical element in the glass;

exposing at least one portion of the photosensitive glass substrate to an activating energy source;

exposing the photosensitive glass substrate to a heating phase of at least ten minutes above its glass transition temperature;

cooling the photosensitive glass substrate to transform at least a portion of the exposed photosensitive glass substrate to a crystalline material to form a glass-crystalline substrate; and

etching the glass-crystalline substrate with an etchant solution to form the one or more micro-lens device(s).

3. The method of claims 1 or 2 wherein the optical coupler or the optical element comprises one or more micro-lenses.

4. The method of any of claims 1 to 3 wherein the photosensitive glass substrate comprises 60 - 76 weight % silica; at least 3 weight % K_2O with 6 weight % - 16 weight % of a combination of K_2O and Na_2O; 0.003 - 1 weight % of at least one oxide selected from the group

consisting of Ag_2O and Au_2O; 0.003 - 2 weight % Cu_2O; 0.75 weight % - 7 weight % B_2O_3, and 6 - 7 weight % Al_2O_3; with the combination of B_2O_3 and $A_{l2}O_3$ not exceeding 13 weight %; 8-15 weight % Li_2O; and 0.001 – 0.1 weight % CeO_2.

5. The method of any of claims 1 to 4 wherein the optical coupler or the optical element is circular with a high optical density on the perimeter and low optical density in the center.

6. The method of any of claims 1 to 5 wherein the optical coupler or the optical element is a micro-lens comprising a high optical density on the perimeter and a low optical density in the center.

7. The method of any of claims 1 to 6 wherein the optical coupler or the optical element provides the optical power.

8. The method of any of claims 1 to 7 wherein the halftone design provides the optical power of the optical coupler or the optical element.

9. The method of any of claims 1 to 8 wherein the optical coupler or the optical element comprises a pattern of high optical density with concentric circles.

10. The method of any of claims 1 to 9 wherein the optical coupler or the optical element comprises a diffractive pattern of concentric circles.

11. The method of any of claims 1 to 10 wherein the optical coupler or the optical element forms a diffractive optical micro-lens.

12. The method of any of claims 1 to 11 wherein the pattern of concentric circles provides the optical power of the optical coupler or the optical element.

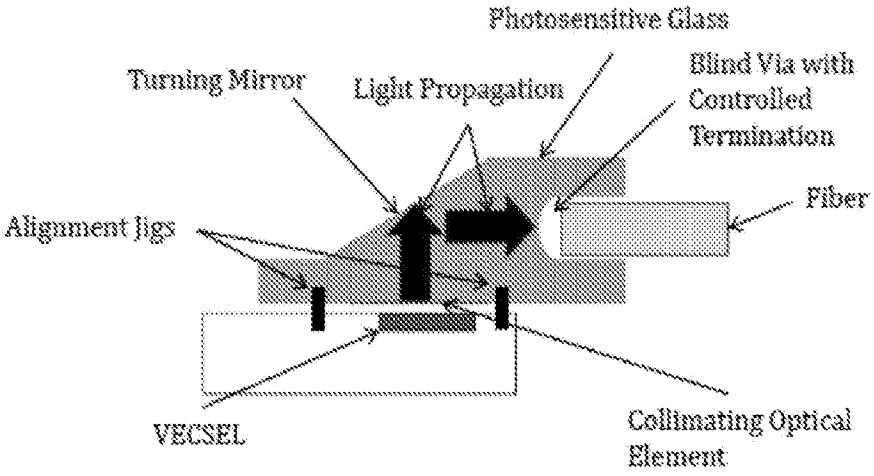


FIGURE 1

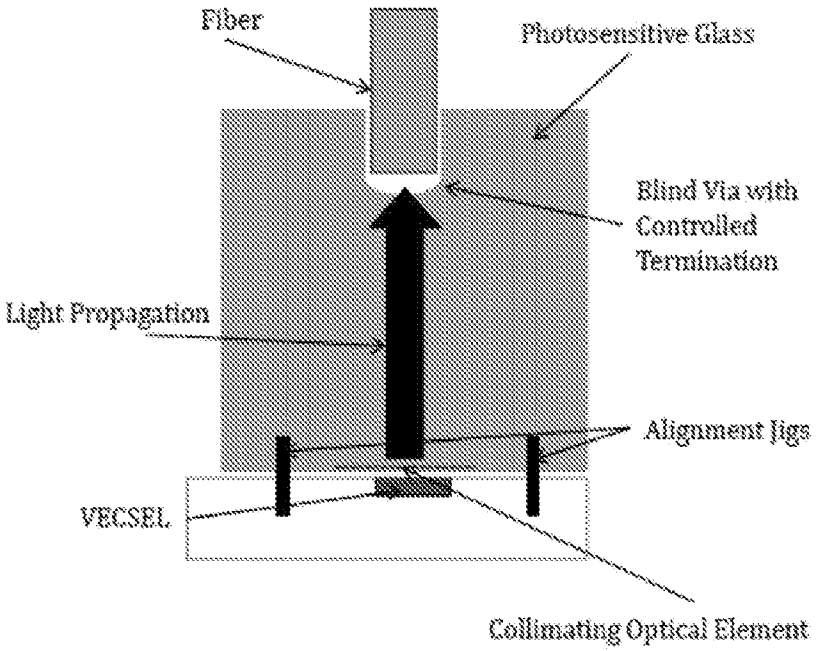


FIGURE 2

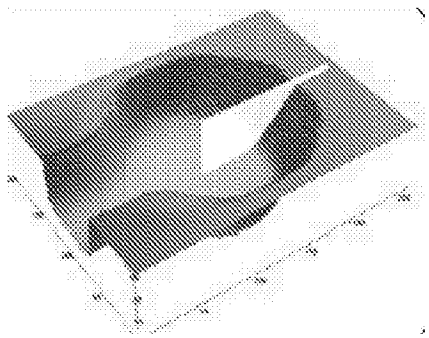


FIGURE 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/026662

A. CLASSIFICATION OF SUBJECT MATTER

G02B 1/00 (2006.01) C03C 3/04 (2006.01) C03C 3/083 (2006.01) C03C 3/095 (2006.01) C03C 4/04 (2006.01) G02B 3/00 (2006.01) G02B 3/08 (2006.01) G02B 6/26 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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: PATENW (EPODOC, WPIAP and TXTE). Search terms: G03B 3/0087 (CPC); C03C 4/04 (and sub-marks in IPC and CPC); G02B 5/1857 (CPC); G02B 5/1876 (and sub-marks in IPC and CPC); G01N 2201/0866 (CPC); G02B 13/001 (and sub-marks in IPC and CPC); optic; G02B (IPC and CPC); C03C (IPC and CPC); glass; photosensitive; light, radiation; sensitive; C03C 3/04 (and sub-marks in IPC and CPC); silica, silicon dioxide; quartz, silicate; lithium oxide; aluminium oxide, alumina; cerium oxide; mask, lithography; expose, irradiate; heat, anneal; cool, quench; crystallise; etch; couple, inter-connect; APEX, FOTURAN; half-tone, gray-tone; digital mask; AND LIKE TERMS. Database: Espacenet. Search terms: 3D Glass Solutions, Inc (Applicant); FLEMMING, Jeb H (Inventor), BULLINGTON, Jeff (Inventor), CHENOWETH, Luis C (Inventor), COOK, Roger (Inventor); coupler; G02B (IPC); C03C (IPC); G02B 3/0087 (CPC); G02B 5/1876 (CPC); G02B 5/188 (CPC); G02B 5/1885 (CPC); G02B 5/189 (CPC); G02B 5/1895 (CPC); G02B 5/1857 (CPC); G02B 13/-- (CPC); G02B 3/-- (CPC); C03C 4/04 (IPC); C03C 4/06 (IPC); AND LIKE TERMS. Database: Auspat. Search terms: 3D Glass Solutions, Inc (Applicant); FLEMMING, Jeb H (Inventor), BULLINGTON, Jeff (Inventor), CHENOWETH, Luis C (Inventor), COOK, Roger (Inventor); lens, microlens; photosensitive; optic; glass; AND LIKE TERMS. Applicant and Inventor names searched in internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

[X] Further documents are listed in the continuation of Box C [X] 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

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"O" document referring to an oral disclosure, use, exhibition or other means

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"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
5 June 2017	05 June 2017
Name and mailing address of the ISA/AU	**Authorised officer**
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustralia.gov.au	Richard Baker AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262832583

INTERNATIONAL SEARCH REPORT C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		International application No. **PCT/US2017/026662**
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2015/112903 A1 (3D GLASS SOLUTIONS, INC) 30 July 2015 Abstract, last paragraph starting on page 1 and continuing onto page 2, last paragraph starting on page 5 to first paragraph starting on page 6, claims 1, 3 and 7 to 11	1-12
X	US 2015/0277047 A1 (LIFE BIOSCIENCE, INC.) 01 October 2015 Abstract, paragraphs 0005, 0024, 0056, 0075 to 0076 and 0096 to 0097	1-12
X	WO 2008/119080 A1 (LIFE BIOSCIENCE INC.) 02 October 2008 Abstract, page 1 line 28 to page 2 line 28, page 6 lines 22 to 30, page 10 lines 18 to 19, page 15 lines 1 to 31	1-12
X	US 2011/0217657 A1 (FLEMMING et al.) 08 September 2011 Abstract, paragraphs 0040, 0109 to 0111 and 0113 to 0120	1-12
X	US 2011/0195360 A1 (FLEMMING et al.) 11 August 2011 Abstract, paragraphs 0010, 0034, 0085 to 0087 and 0089 to 0096	1-12

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/US2017/026662**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		**Patent Family Member/s**	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
WO 2015/112903 A1	30 July 2015	WO 2015112903 A1	30 Jul 2015
		EP 3097440 A1	30 Nov 2016
		JP 2017508177 A	23 Mar 2017
		KR 20160140598 A	07 Dec 2016
		US 2017003421 A1	05 Jan 2017
US 2015/0277047 A1	01 October 2015	US 2015277047 A1	01 Oct 2015
		WO 2014043267 A1	20 Mar 2014
WO 2008/119080 A1	02 October 2008	WO 2008119080 A1	02 Oct 2008
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		US 8096147 B2	17 Jan 2012
		US 2008248250 A1	09 Oct 2008
		US 8361333 B2	29 Jan 2013
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		CN 102869630 A	09 Jan 2013
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		US 8709702 B2	29 Apr 2014
		WO 2011100445 A1	18 Aug 2011
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		US 8709702 B2	29 Apr 2014
		CN 102869630 A	09 Jan 2013
		US 2011217657 A1	08 Sep 2011
		WO 2011100445 A1	18 Aug 2011

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.