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(54) **Title**: LIGHT FOCUSING STRUCTURES FOR FIBER OPTIC COMMUNICATIONS SYSTEMS AND METHODS OF FABRICATING THE SAME USING SEMICONDUCTOR PROCESSING AND MICRO-MACHINING TECHNIQUES

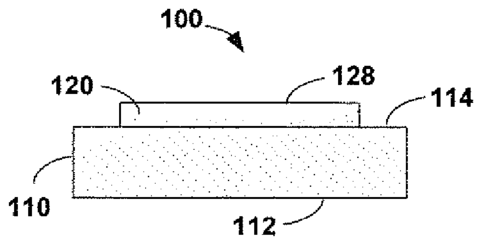

FIG. 1A

(57) **Abstract**: Methods of fabricating light focusing elements for use in a fiber optic communications system are disclosed in which a plurality of light focusing elements are formed on or in a top surface of a substrate. The substrate is then diced to singulate the light focusing elements.

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LIGHT FOCUSING STRUCTURES FOR FIBER OPTIC COMMUNICATIONS SYSTEMS AND METHODS OF FABRICATING THE SAME USING SEMICONDUCTOR PROCESSING AND MICRO-MACHINING TECHNIQUES

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority under 35 U.S.C. § 119(e) from United States Provisional Patent Application Serial No. 61/667,008, filed July 2, 2012, the entire content of which is incorporated herein by reference as if set forth in its entirety.

BACKGROUND

[0002] The present disclosure relates generally to fiber optic communications systems and, more particularly, to methods of mass-producing light focusing structures for such systems using semiconductor processing and micro-machining techniques.

[0003] There are various applications in fiber optic communications systems in which it may be desirable to focus a relatively large area light field into a smaller area light field, or vice versa. As one example, in some applications, it may be desirable to focus an optical signal that is transmitted over a single-mode optical fiber onto a smaller diameter (or other shaped) waveguide structure for purposes of, for example, coupling the optical signal onto an integrated circuit chip. As another example, it may be desirable to focus a larger area light field that is output by an optical source onto a smaller area optical transmission path such as an optical fiber or an optical waveguide.

SUMMARY

[0004] Pursuant to embodiments of the present invention, methods of fabricating light focusing elements for use in fiber optic communications system are provided. Pursuant to these methods, a plurality of light focusing elements are formed on a substrate. The substrate is then diced to singulate the light focusing elements for use in a fiber optic communications system.

[0005] In some embodiments, the light focusing elements may be graded index structures such as, for example, graded index waveguides In other embodiments, the light focusing elements may be Fresnel lens. The light focusing elements may be formed using, for example, photolithography processes to etch a top surface of the substrate or one or more layers that are deposited on the top surface of the substrate. In other embodiments, the light focusing elements may be formed via laser micro-machining.

[0006] Pursuant to further embodiments of the present invention, wafers are provided that include a substrate that has a plurality of light focusing elements on an upper surface thereof. A plurality of scribe lines are provided on the wafer that separate the light focusing elements into rows and columns. Each light focusing element on the wafer may be configured to focus a large area light field that is incident in a direction that is generally normal to the top surface of the substrate into a smaller area light field.

[0007] Pursuant to still further embodiments of the present invention, methods of fabricating light focusing elements for use in a fiber optic communications system are provided in which a plurality of diffractive patterns are formed on a substrate via at least one of lithography, dry etching, wet etching, laser micromachining or nano-machining to form a plurality of light focusing elements on the substrate. The substrate is then diced to singulate the light focusing elements .

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] **FIG. 1A** is schematic side view of a light focusing element according to embodiments of the present invention.

[0009] **FIG. 1B** is a schematic plan view of the light focusing element of **FIG. 1A**.

[0010] **FIG. 1C** is a cross-sectional view taken along the line **1C--1C** of **FIG. 1B**.

[0011] **FIG. 1D** is a schematic plan view of a substrate that includes a plurality of the light focusing structures of **FIGS. 1A-1C**.

[0012] **FIG. 1E** is a schematic side view of a modified version of the light focusing element of **FIGS. 1A-1C** that includes a reflective layer so that the light focusing element may operate in a reflective mode.

[0013] **FIG. 1F** is a schematic plan view of a light focusing element according to further embodiments of the present invention.

[0014] **FIG. 1G** is a cross-sectional view taken along the line **1G—1G** of **FIG. 1F**.

[0015] **FIGS. 2A-2C** are cross-sectional diagrams that illustrate processes according to embodiments of the present invention that may be used to fabricate the substrate of **FIG. 1D**.

[0016] **FIG. 3A** is a schematic plan view of a light focusing element according to further embodiments of the present invention.

[0017] **FIG. 3B** is a cross-sectional view taken along the line **3B—3B** of **FIG. 3A**.

[0018] **FIG. 3C** is a graph that illustrates the refractive index of the various layers of the graded index structures included in the light focusing element of **FIGS. 3A-3B**.

[0019] **FIG. 3D** is a schematic plan view of a substrate that includes a plurality of the light focusing structures of **FIGS. 3A-3B**.

[0020] **FIGS. 4A** and **4C** are schematic plan views, and **FIGS. 4B** and **4D** are cross-sectional views taken along the lines **4B—4B** and **4D—4D** of **FIGS. 4A** and **4C**, respectively, that together illustrate an example method of fabricating the light focusing element of **FIGS. 3A-3B**.

[0021] **FIG. 5A** is schematic end view of a light focusing element according to yet further embodiments of the present invention.

[0022] **FIG. 5B** is a schematic plan view of the light focusing element of **FIG. 5A**.

[0023] **FIG. 5C** is a schematic side view of the light focusing element of **FIG. 5A**.

[0024] **FIG. 5D** is a graph that illustrates the refractive index of the various layers of the graded index waveguide included in the light focusing element of **FIGS. 5A-5C**.

[0025] **FIG. 6A** is schematic end view of a light focusing element according to additional embodiments of the present invention.

[0026] **FIG. 6B** is a schematic plan view of the light focusing element of **FIG. 6A**.

[0027] **FIG. 6C** is a schematic side view of the light focusing element of **FIG. 6A**.

[0028] **FIG. 7A** is a plan view of a light focusing element according to still further embodiments of the present invention.

[0029] **FIG. 7B** is a cross-sectional view of the light focusing element of **FIG. 7A** taken along line **7B—7B** of **FIG. 7A**.

[0030] **FIG. 8A** is a schematic plan view of a light focusing element according to yet another embodiment of the present invention.

[0031] **FIG. 8B** is a cross-sectional view of the light focusing element of **FIG. 8A** taken along line **8B—8B** of **FIG. 8A**.

[0032] **FIG. 8C** is a schematic diagram illustrating how the light focusing element of **FIGS. 8A-8B** may be used to couple optical signals from a first multi-core optical fiber to a second multi-core optical fiber.

[0033] **FIG. 8D** is a schematic diagram illustrating how the light focusing element of **FIGS. 8A-8B** may be used to couple optical signals from a plurality of waveguides onto a multi-core optical fiber.

[0034] **FIG. 8E** is a schematic diagram illustrating how the light focusing element of **FIGS. 8A-8B** may be used to couple the outputs of multiple optical sources onto a multi-mode optical fiber.

DETAILED DESCRIPTION

[0035] Pursuant to embodiments of the present invention, methods of using semiconductor processing and/or micro-machining techniques to mass-produce light focusing elements for fiber optic communications systems are disclosed. Pursuant to some of these methods, semiconductor growth and patterning processes may be used to grow hundreds, thousands or even tens of thousands of light focusing elements on a single substrate. The substrate may then be singulated into individual light focusing elements using standard semiconductor scribing/dicing techniques. Pursuant to other embodiments, semiconductor patterning techniques may be used to pattern a substrate in a manner that forms hundreds, thousands or even tens of thousands of light focusing elements on the substrate. In still further embodiments, laser micro-machining techniques, two-photon polymerization techniques and/or other material modification techniques may be used to mass-produce large numbers of light focusing elements on a substrate, which may then be singulated into individual light focusing elements. In some embodiments, the light focusing elements may be configured to focus a light field that is received in a plane that is generally perpendicular to the substrate on which the light focusing elements are formed such that the light field travels through the substrate from a top surface to a bottom surface thereof.

[0036] A wide variety of light focusing elements may be formed using the techniques according to embodiments of the present invention including, for example, Fresnel lenses, other refractive light focusing structures, graded index structures, graded index waveguides, other photonic waveguides and the like. Embodiments of the present invention will now be discussed in detail with reference to the attached drawings, in which certain embodiments of the invention are shown

[0037] **FIGS. 1A-1C** illustrate a light focusing element **100** according to certain embodiments of the present invention. In particular, **FIG. 1A** is schematic side view of the light focusing element **100, FIG. 1B** is a schematic plan view of the light focusing element **100**, and **FIG. 1C** is a cross-sectional view of the light focusing element **100** taken along the line **1C--1C** of **FIG. 1B**.

[0038] Referring to **FIGS. 1A-1C**, the light focusing element **100** includes a substrate **110** that has a bottom surface **112** and a top surface **114**. A light focusing structure in the form of Fresnel lenses **120** is disposed on the top surface **114** of the substrate **110**. The substrate **110** may comprise, for example, a semiconductor substrate such as a silicon substrate, a silicon carbide substrate, etc. or a non-semiconductor substrate such as, for example, a sapphire substrate, a silica substrate, etc., or a combination of both semiconductor and non-semiconductor substrates such as a silicon-on-insulator substrate. The substrate **110** may be transparent at a particular wavelength or range of wavelengths (i.e., for the range of wavelengths for optical signals that are to be focused by the Fresnel lens **120**). For example, in some embodiments, the substrate 110 may be transparent for at least a range of wavelengths from about 830 nm to about 1360 nm. Herein, a "transparent" substrate refers to a substrate that passes at least about 90% of light that is incident thereon. As discussed below, in other embodiments (e.g., embodiments in which the Fresnel lens **120** operates in a reflective mode) the substrate **110** need not be transparent at a range of wavelengths of interest and may, instead, be reflective at the range of wavelengths of interest.

[0039] As is best shown in **FIGS. 1B** and **1C**, each Fresnel lens **120** includes a plurality of concentric annular sections **122** that are sometimes referred to as "Fresnel zones." Each Fresnel zone **122** may have an angled outer surface **124**, and stepwise discontinuities may be provided between adjacent Fresnel zones **122** (see **FIG. 1C**). The angle of the outer surface **124** of each Fresnel zone **122** may be different in order to focus light that is incident on the Fresnel lens **120** to a smaller area light field. The Fresnel lens **120** has a lower surface **126** that may be directly on the upper surface **114** of the substrate **110**, and an upper surface **128** which comprises the outer surfaces **124** of the Fresnel zones **122**. A central portion of the Fresnel lens **120** may have the shape of a standard lens. As shown in **FIG. 1B**, the Fresnel zones **122** may become increasingly thinner the further they are from the center of the Fresnel lens **120**. In some embodiments, all of the Fresnel zones **122** may be formed integrally from a single piece of material. In other embodiments, the Fresnel zones **122** may be formed from different materials. In some embodiments, the substrate **110** and the Fresnel lens **120** may comprise different materials. In other embodiments, the substrate **110** and the Fresnel lens **120** may be formed of the same material. In some of these embodiments, the Fresnel lens **120** may be formed by patterning the substrate **110** by, for example, photolithography or micro-machining processes, to form the Fresnel lens **120** in or on the upper surface **114** of the substrate **110**.

[0040] Light such as an optical signal that is incident on the upper surface **128** of the Fresnel lens **120** passes through the Fresnel lens **120** and is focused into a smaller area light field. In some embodiments, the substrate **110** may be removed after the Fresnel lens **120** is fabricated using, for example, a grinding process, a chemical-mechanical polishing process and/or an etching process. In other embodiments, the substrate **110** may be left in place.

[0041] **FIG. 1D** is a schematic plan view of a portion of a substrate **150** that includes a plurality of Fresnel lens **120** that are disposed thereon. The substrate **150** may be identical to the substrate **110** that is described above, except that the substrate **150** may be much larger so that a plurality of Fresnel lens **120** may be fabricated thereon. The substrate **150** may include scribe lines **152** that run in rows and columns between the Fresnel lens **120**. After the Fresnel lens **120** are formed in or on the substrate **150**, the substrate **150** may be singulated by dicing the substrate **150** along the scribe lines **152** to create a plurality of the individual light focusing elements **100** of **FIGS. 1A-1C**. While **FIG. 1D** depicts a total of eighteen Fresnel lenses **120** on the portion of the substrate that is illustrated, it will be appreciated that very large numbers of Fresnel lenses **120** may be fabricated on a single substrate using the techniques disclosed herein.

[0042] While in the embodiment of **FIGS. 1A-1D** the Fresnel lens **120** comprises a circular structure, it will be appreciated that numerous other designs for the Fresnel lens **120** may be used that do not have generally circular shapes. Thus, it will be appreciated that the Fresnel lens **120** may be modified from what is shown in **FIGS. 1A-1D** to have any appropriate shape that uses diffraction to perform desired beam shaping for a received light field.

[0043] Typically, the Fresnel lens **120** will be designed to operate in a diffractive mode. However, it will be appreciated that, in some embodiments, it may be desirable to form Fresnel lenses **120** that operate in a reflective mode. In such embodiments, the substrate **110** may be formed of a material that reflects, as opposed to transmits, optical signals of the wavelength of interest. In other embodiments, one or more reflective layers may be provided on the substrate **110** that reflect an incident optical signal. These reflective layers may be positioned, for example, on the bottom surface **112** of the substrate **110** or on the top surface **114** of the substrate **110**. **FIG. 1E** is a schematic side view of a portion of a light focusing element **100'** that includes a substrate **110** that includes a Fresnel lens **120** thereon. A reflective layer **130** is provided between the substrate **110** and the Fresnel lens **120** that allows the light focusing element **100'** to operate in a reflective mode.

[0044] As noted above, in some embodiments, the light focusing elements **100** and **100'** may be fabricated using semiconductor growth and/or processing technologies. By way of example, one or more epitaxial layers may be epitaxially grown or deposited on the substrate **110** via metal organic chemical vapor deposition, sputtering, laser deposition, plasma deposition or other semiconductor growth or deposition techniques. These layers may be selectively grown and/or non-selectively grown and then patterned using photolithography or other semiconductor patterning techniques to form the Fresnel lens **120** in or on the substrate **110**. In other embodiments, the substrate **110** may simply be etched using photolithography techniques, laser micro or nanomachining or other patterning techniques to etch away portions of the top surface **114** of substrate **110** to form the Fresnel lens **120**.

[0045] **FIGS. 1F-1G** illustrate a modified version **100'** of the light focusing element **100** of **FIGS. 1A-1E**. In particular, **FIG. 1F** is a schematic plan view of the light focusing element **100'** and **FIG. 1G** is a cross-sectional view of the light focusing element **100'** taken along the line **1G—1G** of **FIG. 1F**.

[0046] It will be appreciated that the curved surfaces (e.g., the angled outer surfaces **124**) that are included in the Fresnel lens **120** of the light focusing element **100** may be more difficult to manufacture using certain semiconductor growth and/or processing technologies. Accordingly, pursuant to further embodiments of the present invention, light focusing elements may be provided that omit such curved surfaces. Such embodiments may be referred to herein as "binary" Fresnel lenses.

[0047] For example, as shown in **FIGS. 1F-1G**, the light focusing element **100'** includes a binary Fresnel lens **120'**. In particular, as shown in **FIG. 1G**, the light focusing element **100'** includes a substrate **110** that has a light focusing structure in the form of Fresnel lenses **120'** disposed on the top surface thereof. The substrate **110** may be identical to the substrate **100** of **FIGS. 1A-1E** and hence will not be described further herein.

[0048] As shown in **FIGS. 1F** and **1G**, the Fresnel lens **120'** includes a plurality of Fresnel zones **122'**. However, in contrast to the Fresnel zones **122** of the light focusing element **100**, the Fresnel zones **122'** do not have angled outer surfaces, but instead are simply formed using a plurality of concentric rings. The Fresnel zones **122'** may become increasingly narrower the farther they are from the center of the Fresnel lens **120'**, and the spacings between adjacent Fresnel zones **122'** may also decrease the farther they are from the center of the Fresnel lens **120'**. This arrangement may act to focus light that is incident on the Fresnel lens **120'** to a smaller area light field. The light focusing may not be as effective as the light focusing that may be obtained with the Fresnel lens **120** of the light focusing element **100**, but may still be sufficient for many applications, and may be more easily manufactured. The Fresnel zones **122'** may be formed from a single piece of material or from different materials. The Fresnel lens **120'** may be formed by any of the techniques, discussed above, that may be used to form the Fresnel lens **120**, and the Fresnel lens **120'** will operate in the same manner as the Fresnel lens **120** to focus light into a smaller area light field. It will also be appreciated that the Fresnel lens **120'** may be used in place of the Fresnel lens **120** in the substrate **150** of **FIG. 1D**, and that the Fresnel lens **120'** may also be configured to operate in either a transmissive diffraction mode or a reflective diffraction mode.

[0049] **FIGS. 2A-2C** illustrate processes according to embodiments of the present invention that may be used, for example to fabricate the substrate **150** of **FIG. 1D**. To simplify the drawings, **FIGS. 2A-2C** only illustrate a cross-section of a portion of one of the light focusing structures of **FIG. 1D**.

[0050] As shown in **FIG. 2A**, a photoresist layer **160** may be deposited onto a substrate **110** that includes a Fresnel lens formation layer **121** thereon. As shown in **FIG. 2B**, light **170** from a light source **172** is then used to transfer a geometric pattern from a photomask **162** onto the photoresist **160** to form a patterned photoresist **164**. The patterned photoresist **164** includes a plurality of openings **166** that selectively expose portions of the Fresnel lens formation layer **121**. Then, referring to **FIG. 2C**, standard semiconductor etching techniques including, for example, plasma etching, wet etching, dry etching, high energy ion beam etching, electron beam etching, deep reactive ion etching and the like may be used to pattern the Fresnel lens formation layer **121** into a desired shape such as, for example, into the shape of a Fresnel lens **120**. Typically, a series of photolithography processes are performed to form, for example, the curved outer surfaces of each Fresnel zone **122**. As photolithography and etching techniques are well known in the art, the example of **FIG. 2** only illustrates the first of the etching steps. It will be appreciated, however, that a plurality of photolithography steps would typically be performed to fabricate the substrate **150** of **FIG. 1D**.

[0051] While the example embodiment described with respect to **FIGS. 2A-2C** includes a Fresnel lens formation layer **121** on the substrate **110**, it will be appreciated that, in other embodiments, the Fresnel lens formation layer **121** may be omitted and the Fresnel lens **120** may be etched directly into the substrate **110**. It will also be appreciated that the Fresnel lens formation layer **121** may comprise a multi-layer structure.

[0052] In other embodiments, laser micro-machining techniques may be used instead of photolithography to pattern the substrate **110** (or the substrate **110** including one or more epitaxial or other layers that are deposited or grown thereon) to form the plurality of Fresnel lenses **120** included on the substrate **150** of **FIG. 1D**. In still other embodiments, ion-beam etching may be used without the use of photolithography masks. In still other embodiments, two-photon polymerization growth processes may be used to form the Fresnel lenses **120**. Pursuant to these two-photon polymerization processes, a gel such as a polymer gel or a silica gel may be deposited on the substrate **110**. A laser may then be controlled to send photons through the gel which induce a chemical reaction that cross-links the gel to form a solid such as, for example, solid glass (in the case of a silica gel). The non-cross-linked gel may then be washed or drained away. The laser may be controlled to only cross-link portions of the gel that form structures having a desired shape from the gel on the substrate **110**. In each case, the above-described processing techniques may be used to form a large number of Fresnel lens **120** on a single substrate which may subsequently be diced into individual light focusing elements. Thus, it will be appreciated that any of the above-described techniques may be used to mass produce light focusing elements at low cost.

[0053] While the embodiments discussed above with respect to **FIGS. 1A-1E** and **FIGS. 2A-2C** illustrate the formation of one or more Fresnel lenses **120** on a substrate **110/150**, it will be appreciated that according to other embodiments of the present invention diffractive structures other than Fresnel lenses may be formed on or in the substrate **110/150**. For example, instead of Fresnel lenses, diffractive structures can be fabricated on the substrate **110/150** such that specific optical intensity or field patterns (e.g., annular, dot matrix etc.) can be produced by incident light.

[0054] Pursuant to further embodiments of the present invention, graded index structures or lenses may be formed on a substrate using semiconductor processing or other mass-production techniques. **FIGS. 3A-3D** are various views illustrating one or more light focusing elements **200** according to embodiments of the present invention that are implemented using graded index structures. In particular, **FIG. 3A** is a schematic plan view of one of the light focusing elements **200**. **FIG. 3B** is a cross-sectional view of the light focusing element **200** taken along the line **3B—3B** of **FIG. 3A**. **FIG. 3C** is a schematic graph illustrating the refractive index of a graded index structure included in the light focusing element **200** of **FIGS. 3A-3B**. Finally, **FIG. 3D** is a schematic plan view of a substrate **250** that includes a plurality of the light focusing structures **200** fabricated thereon.

[0055] As shown in **FIGS. 3A-3B**, the light focusing element **200** comprises a plurality of concentric rings of material **230** (which are labeled individually as **231-237** in the figures) that are formed on a top surface of a substrate **210** to provide the graded index structure **220**. Each of the concentric rings **230** may have a different refractive index "n" (e.g., n1, n2, n3, etc.). As shown in **FIG. 3C**, the refractive index of the materials used to form the concentric rings **230** increases the closer the concentric rings **230** are to the center of the graded index structure **220**. The substrate **210** may comprise, for example, a semiconductor substrate such as a silicon substrate, a silicon carbide substrate, etc. or a non-semiconductor substrate such as, for example, a sapphire substrate, a silica substrate, etc. or a combination thereof such as a silicon-on-insulator substrate. The substrate **210** may be transparent at a particular wavelength or range of wavelengths.

[0056] The graded index structure **220** may be used to focus a large area light field into a smaller area light field. The graded index structure **220** may focus light that is incident in a direction that is generally normal to the top surface **214** of the substrate **210**. Thus, the light that is focused by the graded index structure **220** passes through the substrate **210**. The variation in the refractive index of the concentric rings of material **230** focuses the large area light field as the light field passes through the graded index structure **220** (or alternatively, disperses a small area light field that is passed through the graded index structure **220** in the opposite direction into a larger area light field).

[0057] The light focusing structure **200** of **FIGS. 3A** and **3B** may be formed by using circular masks in a series of growth processes (e.g., an MOCVD growth process, a sputtering process, a laser deposition processes, plasma deposition processes, etc.) to selectively grow the concentric rings of material **230** that have different refractive indices. In other embodiments, the substrate **210** or a layer (not shown in the figures) that is deposited on the substrate **210** may be modified using material modification techniques to form the concentric rings of material **230** that have different refractive indices. For example, a layer of material may be deposited on the substrate **210** which has a diffractive index that changes in response to exposure to a laser. Masks may be used to selectively exposes concentric rings of this material to a laser beam such that the laser beam can modify each concentric ring of material to have a desired refractive index. Thus, it will be appreciated that the graded index structure **220** may be formed in a variety of different ways.

[0058] **FIG. 3D** is a schematic plan view of a portion of a substrate **250** that includes a plurality of graded index structures **220** disposed thereon. The substrate **250** may be identical to the substrate **210** that is described above, except that the substrate **250** may be much larger so that a large number of graded index structures **220** may be formed on a single substrate. The substrate **250** may include scribe lines **252** that run in rows and columns between the graded index structures **220**. After the graded index structures **220** are formed on the substrate **250**, the substrate **250** may be diced along the scribe lines **252** to create a plurality of individual light focusing elements **200**. While **FIG. 3D** depicts a total of nine graded index structures **220** on the portion of the substrate **250** that is illustrated, it will be appreciated that very large numbers of graded index structures **220** may be fabricated on the substrate **250** using the techniques disclosed herein.

[0059] While in the embodiment of **FIGS. 3A-3D** the graded index structures **220** each comprise a circular structure, it will be appreciated that numerous other designs may be used, including far more complex structures that have desired beam shaping or beam forming properties. It will also be appreciated that the graded index structures **220** may be designed to operate in a reflective mode as well. It will further be appreciated that inverted graded index structures may be provided in which the refractive index is larger for the outer concentric rings of material **230** and smaller for the inner concentric rings of material **230**.

[0060] **FIGS. 4A-4D** illustrate an example method of fabricating the light focusing element **200** of **FIGS. 3A-3B**. In particular, **FIGS. 4A** and 4C are schematic plan views of the light focusing element **200**, while **FIGS. 4B** and **4D** are cross-sectional diagrams taken along the line **4B—4B** of **FIG. 4A** and along the line **4D—4D** of **FIG. 4C**, respectively.

[0061] Referring to **FIGS. 4A** and **4B**, a first mask layer (not shown) may be deposited on the substrate **210** and may be patterned using, for example, conventional semiconductor processing photolithography techniques to create a first mask **260** that has a circular opening **262** that exposes the substrate **210**. A first material layer (not shown) may then be deposited on the first mask **260** and in the first opening **262** in the first mask **260**, and a planarizing technique such as a chemical-mechanical polishing technique may be used to remove all portions of the first material layer except for the portion **264** that is deposited in the first opening **262**. The first material layer may have a first refractive index n1. A stripping or other conventional process may then be used to remove the first mask **260**.

[0062] Referring to **FIGS. 4C** and **4D**, a second mask layer (not shown) may be deposited on the substrate **210** and the remaining portion **264** of the first material layer. The second mask layer may be patterned using, for example, conventional semiconductor processing photolithography techniques to create a second mask **270** that has an annular opening **272** that exposes the substrate **210**. A second material layer (not shown) may then be deposited on the second mask **270** and in the second annular opening **272** in the second mask **270**, and a planarizing technique such as a chemical-mechanical polishing technique may be used to remove all portions of the second material layer except for the portion **274** that is deposited in the second annular opening **272**. The second material layer may have a second refractive index n2 that is less than the refractive index n1. A stripping or other conventional process may then be used to remove the second mask **270**.

[0063] The same process described above to form the concentric ring of material **274** may be used to form additional concentric rings of material that have larger diameters to complete the light focusing element **200** illustrated in **FIGS. 3A** and **3B**.

[0064] Pursuant to still further embodiments of the present invention, light focusing elements are provided that incorporate graded index waveguide technology. **FIGS. 5A-5C** illustrate one such light focusing element **300**. In particular, **FIG. 5A** is schematic end view of the light focusing element **300**, **FIG. 5B** is a schematic plan view of the light focusing element **300**, and **FIG. 5C** is a schematic side view of the light focusing element **300**. **FIG. 5D** is a graph that illustrates the refractive index of the various layers of the graded index waveguide included in the light focusing element **300**.

[0065] As shown in **FIGS. 5A-5C**, the light focusing element **300** comprises a graded index waveguide **320** that is provided on a substrate **310**. The graded index waveguide **320** comprises a series of half-cylinder structures **330** (which are labeled individually as **331-335** in the figures) that are longitudinally arranged on a top surface **314** of the substrate **310**. The smallest of the structures **330** (structure **331**) is on the right side of the substrate and the largest structure (structure **335**) is on the left side of the substrate **310**, and the structures **330** decrease in size as you move from the left to the right in the view of **FIG. 5C**. Each of the structures **331-335** may have a different refractive index "n" (see **FIG. 5C**) with the refractive index of the structures **331-335** increasing the smaller the size of the structure (i.e., $n1 > n2 > n3 > n4 > n5$). This is graphically illustrated in **FIG. 5D**. The substrate **310** may comprise, for example, a semiconductor substrate such as a silicon substrate, a silicon carbide substrate, etc. or a non-semiconductor substrate such as, for example, a sapphire substrate, a silica substrate, etc. or a combination thereof such as a silicon-on-insulator substrate.

[0066] The graded index waveguide **320** may be used to focus a large area light field into a smaller area light field. The variation in the refractive index of the materials used to form the structures **331-335** focuses the large area light field as the light field passes through the graded index waveguide **320** in a direction parallel to the top surface **314** of the substrate **310**.

[0067] In some embodiments, the light focusing element **300** of **FIGS. 5A-5C** may be formed using semiconductor growth and photolithography techniques to grow and pattern the graded index waveguide **320** on the substrate **310**. In other embodiments, the substrate **310** and/or a layer (not shown in the figures) that is deposited on the substrate **310** may be modified using material modification techniques (and possibly patterned as well using, for example, photolithography techniques) to form the structures **331-335** that have different indexes of refraction. For example, a layer of material may be deposited on the substrate **310** which has a refractive index that changes in response to exposure to a laser. Masks may be used to selectively expose portions of this material to a laser beam such that the laser beam can form the structures **331-335** having different refractive indexes. Thus, it will be appreciated that the graded index waveguide **320** may be formed in a variety of different ways.

[0068] **FIGS. 6A-6C** illustrate a light focusing element **400** according to further embodiments of the present invention. In particular, **FIG. 6A** is schematic end view of the light focusing element **400**, **FIG. 6B** is a schematic plan view of the light focusing element **400** and **FIG. 6C** is a schematic side view of the light focusing element **400**.

[0069] As shown in **FIGS. 6A-6C**, the light focusing element **400** comprises a graded index lens **420** that is provided on a substrate **410**. The graded index lens **420** comprises a series of structures **430** (which are labeled individually as **431-435** in the figures) that are formed on a top surface **414** of the substrate **410**. The smallest of the structures **430** (structure **431**) comprises a half-cylinder structure. The structure **432** is coaxially deposited on top of the structure **431**, and has a half-annular shape. As shown in **FIGS. 6B** and **6C**, the length of structure **432** is less than the length of structure **431** so that structure **431** extends farther to the right in the view of **FIG. 6C** than does the structure **432**. Structures **433-435** are similarly deposited coaxially in order on structures **431** and **432** in the same fashion so that they each also have a half-annular shape, and the length of each structure **431-435** is reduced as compared to the length of the structure **431-435** that is directly underneath it. Each of the structures **431-435** may have a different refractive index "n," with the refractive index of the structures **431-435** increasing the smaller the size of the structure (i.e., $n1 > n2 > n3 > n4 > n5$). The substrate **410** may comprise, for example, a semiconductor substrate such as a silicon substrate, a silicon carbide substrate, etc. or a non-semiconductor substrate such as, for example, a sapphire substrate, a silica substrate, etc. or a combination thereof such as a silicon-on-insulator substrate.

[0070] The graded index lens **420** may be used to focus a large area light field into a smaller area light field. The variation in the refractive index of the materials used to form the structures **431-435** focuses the large area light field as the light field passes through the graded index lens **420** in a direction parallel to a top surface of the substrate **410**.

[0071] In some embodiments, the light focusing structure **400** of **FIGS. 6A-6C** may be formed using semiconductor growth and photolithography techniques to grow and pattern the graded index waveguide **420** on the substrate **410**. In other embodiments, the substrate **410** and/or a layer (not shown in the figures) that is deposited on the substrate **410** may be modified using material modification techniques (and possibly patterned as well using, for example, photolithography techniques) to form the structures **431-435** that have different indexes of refraction. For example, a layer of material may be deposited on the substrate **410** which has a refractive index that changes in response to exposure to a laser. Masks may be used to selectively expose portions of this material to a laser beam such that the laser beam can form the structures **431-435** having different refractive indexes. Thus, it will be appreciated that the graded index lens **420** may be formed in a variety of different ways.

[0072] **FIGS. 7A** and **7B** are, respectively, a plan view and a cross-sectional view (taken along line **7B—7B** of **FIG. 7A**) of a light focusing element **500** according to still further embodiments of the present invention.

[0073] As shown in **FIGS. 7A** and **7B**, the light focusing element **500** comprises an array **520** of inverted conical structures **522** that are formed on or in a top surface **514** of a substrate **510**. The array **520** of inverted conical structures **522** may focus light that is incident on the array in a direction that is generally normal to the top surface **514** of the substrate **510**. The substrate **510** may comprise, for example, a semiconductor substrate such as a silicon substrate, a silicon carbide substrate, etc. or a non-semiconductor substrate such as, for example, a sapphire substrate, a silica substrate, etc. or a combination thereof such as a silicon-on-insulator substrate. Multi-layered substrates **510** may be used, and the multiple layers may have the same refractive index or different refractive indexes. The substrate **510** may be transparent at a particular wavelength or range of wavelengths. While in the embodiment of **FIGS. 7A** and **7B** the inverted conical structures **522** comprise structures having circular cross-sections, it will be appreciated that conical structures with other cross-sections (e.g., square cross-sections) may alternatively be used. It will likewise be appreciated that tapered structures that are non-conical may be used in place of the inverted conical structures **522** depicted in **FIGS. 7A** and **7B**.

[0074] In some embodiments, the array **520** of inverted conical structures **522** may be formed by patterning the substrate **510** using photolithography or similar patterning processes. In other embodiments, the array **520** of inverted conical structures **522** may be formed by patterning the substrate **510** using laser-machining or micro-machining techniques. Any of the other techniques for forming light focusing elements that are disclosed herein may also be used. In some embodiments, the array may be formed by directly patterning the substrate **510**, while in other embodiments, one or more layers or patterns may be grown or otherwise deposited on the substrate **510** and these layer(s) may then be patterned to form the array **520** of inverted conical structures **522**.

[0075] Light such as an optical signal that is incident on the upper surface **528** of the array **520** passes through the array **520** and is focused into a smaller area light field. In some embodiments, at least part of the substrate **510** may be removed after the array **520** is fabricated using, for example, a grinding process, a chemical-mechanical polishing process and/or an etching step. In other embodiments, the substrate **510** may be left in place. While not depicted in the figures, it will be appreciated that a large plurality of arrays **520** may be formed on a single substrate **510**, and this substrate **510** may then be diced to create a large number of individual light focusing elements **500**.

[0076] **FIGS. 8A** and **8B** are, respectively, a plan view and a cross-sectional view (taken along line **8B—8B** of **FIG. 8A**) of a light focusing element **600** according to yet another embodiment of the present invention. The light focusing element **600** uses a plurality of raised structures that appear to have an arbitrary pattern to focus light from one or more large area light fields into respective smaller area light fields.

[0077] As shown in **FIGS. 8A** and **8B**, the light focusing element **600** comprises a substrate **610** that has a raised diffractive structure **620** formed on an upper surface thereof. The diffractive surface **620** may have what appears to be an arbitrary or random pattern, but in fact is a diffractive pattern that is designed to focus light in a specific manner. The pattern may include a number of "islands" of material that extend upwardly from the underlying substrate **610**. These islands may have different shapes and sizes. The diffractive structure **620** may focus light that is incident on the array in a direction that is generally normal to the top surface **614** of the substrate **610**. The substrate **610** may comprise, for example, a semiconductor substrate such as a silicon substrate, a silicon nitride substrate, etc. or a non-semiconductor substrate such as, for example, a sapphire substrate, a silica substrate, etc. or a combination thereof such as a silicon-on-insulator substrate. Multi-layered substrates **610** may be used, and the multiple layers may have the same refractive index or different refractive indexes. The substrate **610** may be transparent at a particular wavelength or range of wavelengths.

[0078] In some embodiments, the diffractive structure **620** may be formed by depositing one or more layers on the substrate **610** and then etching, machining or otherwise removing material to form the diffractive structure **620** that has a plurality of raised areas **625**. In other embodiments, the diffractive structure **620** may be formed by simply etching, machining or otherwise removing material from the substrate **610** to form the diffractive structure **620** in an upper region of the substrate **610**.

[0079] While the pattern of the diffractive structure **620** may appear arbitrary in some embodiments, it may be specifically designed to focus light or change the light field pattern in some predetermined and desirable ways. The pattern of the diffractive structure **620** may be determined using simulation techniques. For example, a particular application may have one or more optical sources that each have a generally known light field output. The goal may be to couple these one or more light fields into one or more other optical transmission or reception mediums that have different areas. Computer simulation programs are available that will start with (typically) a basic pattern and then iteratively vary the pattern in an effort to find specific patterns that do a good job of focusing the light field(s) from the optical source(s) so that they will efficiently couple into the one or more other optical transmission or reception mediums. These computer programs thus provide a technique for identifying diffractive patterns that will efficiently focus an input light field distribution into a desired output light field distribution. Once a diffractive pattern is identified using these computer programs, then any of the semiconductor growth and/or processing techniques and/or machining or other techniques that are discussed above may be used to form a diffractive structure **620** in or on a semiconductor substrate that has the desired diffractive pattern. It will be appreciated that the raised areas **625** may all have the same height above the bottom surface of the substrate **610**, or may have different heights, and that the height of each raised area **625** need not be constant.

[0080] The light focusing element **600** may be particularly well-suited for applications where a plurality of first light fields need to be converted into a plurality of second light fields in a small space. By way of example, as shown in **FIG. 8C**, in some applications, it may be desirable to couple a first multi-core optical fiber cable **630** to a second multi-core optical fiber cable **640** where the size of the cores **650** in the two cables are not the same and/or are not aligned. In such applications, the diffractive structure **620** in the light focusing element **600** of **FIGS. 8A** and **8B** may be designed to focus each core **650** of the first multi-core optical fiber cable **630** to a respective one of the cores **650** of the second multi-core optical fiber cable **640**. Given the small size of the individual cores (e.g., 50-120 microns in diameter), it may be difficult to design a lens based coupler that can efficiently couple the cores **650** of the first cable **630** to the cores **650** of the second cable **640**. The diffractive structure **620**, however, may be used to focus, for example, all of the cores **650** in the first cable **630** to their respective cores **650** in the second cable **640** and hence may simplify the design of a coupler for coupling a first multi-core optical fiber cable **630** to a second multi-core optical fiber cable **640**.

[0081] As another example, as is shown in **FIG. 8D**, in some applications, a plurality of waveguides **670-672** may be provided in a small space and it may be necessary to couple the light fields output by these respective waveguides into other structures such as the cores **681-683** of a multicore optical fiber **680** (or onto other structures such as other waveguides, optical fibers, etc.). Once again, the tight spacing may make it difficult to perform this coupling using traditional lens-based approaches. The light focusing element **600** may again be used to couple (and focus) the multiple light fields output by the waveguides **670-672** into their corresponding transmission media in the structures **681-683**. It will be appreciated that the example of **FIG. 8D** is reversible in that the system could be designed so that the light travelled from the cores **681-683** of the multicore optical fiber **680** to the respective waveguides **670-672** as opposed to travelling in the opposite direction as described above. It will likewise be appreciated that the waveguides **670-672** could be replaced with a plurality of separate optical fibers and/or with a multicore optical fiber, and that the multicore optical fiber **680** could likewise be replaced with a plurality of waveguides and/or separate optical fibers in further embodiments of the present invention.

[0082] As yet another example, research is currently ongoing into transmitting multiple optical signals, each of which may be at the same wavelength, on a single multi-mode optical fiber using space-division multiplexing or Multiple-Input-Multiple-Output (MIMO) techniques. Pursuant to these techniques, each of the plurality of optical signals are launched onto the optical fiber in a different way so that the signals will have different spatial patterns that allow the signals to be distinguished from each other at a receiver. This technique is illustrated graphically in **FIG. 8E**, which shows a plurality of lasers **690-692** being used to launch optical signals that have the same wavelength onto a multimode optical fiber **695**. In order to launch each of the optical signals on top the optical fiber **695** in a different manner, it may be necessary to point the lasers into the optical fiber **695** at different angles. It may be difficult, however, to line up the outputs of the lasers **690-692** in a desired fashion in front of the optical fiber **695** due to space constraints.

[0083] However, pursuant to embodiments of the present invention, a light focusing element **600** having a diffractive structure **620** may be placed between the outputs of the lasers **690-692** and the optical fiber **695** which may be used to focus the light fields output by the lasers **690-692** in a desired fashion so that the optical signal output by each of the respective lasers **690-692** is launched into the optical fiber at the desired angle. By using the light focusing element **600**, it may be possible to position the lasers **690-692** at greater distances, and greater angles, from the optical fiber **695** while still launching the output of each of the lasers **690-692** into the optical fiber **695** at the proper angle to achieve spatial diversity, as is shown graphically in the schematic diagram of **FIG. 8E**. It will be appreciated that the example of **FIG. 8E** is reversible in that the system could be designed so that the light travelled from the optical fiber **695** to a plurality of other elements such as, for example, three optical receivers (which can be depicted graphically simply by changing the direction of the three arrows in **FIG. 8E**).

[0084] The light focusing elements according to embodiments of the present invention may be used in many different applications. In one example application, the light focusing elements may be mounted in optical connectors such as optical couplers and/or optical connector ports. In this application, the light focusing elements may be used, for example, to focus a light field from a larger optical fiber into a smaller optical fiber or to focus a light field from an optical fiber into a smaller light field that may be coupled into an optical waveguide or other optical transmission path. In such embodiments, the light focusing elements can be relatively large (e.g., 50 microns in diameter or more to fit, for example, adjacent to an end of a multi-mode optical fiber) or can be much smaller (e.g., less than one micron in diameter). In other applications, the light focusing elements disclosed herein may be used for coupling multi-mode optical fibers to small area, high speed photodetectors, for coupling a multi-mode MPO connector to single-mode optical fibers and for coupling an array of multi-mode optical fibers (e.g., a multi-mode MPO connector) to a single multicore optical fiber or to a single-mode MPO connector within a very small form factor. As yet another example, the light focusing elements according to embodiments of the present invention may be used to couple the output of a vertical cavity surface emitting laser ("VCSEL") onto a multi-mode optical fiber. The light focusing elements according to embodiments of the present invention may be able to more effectively couple the output of such VCSEL devices into desired areas of a multi-mode optical fiber which can increase the bandwidth that can be supported by the multi-mode optical fiber.

[0085] In some embodiments, the light focusing elements disclosed herein may be used as an optical mode field converter to compress a large area light field that is output from a multi-mode optical to a small area light field that is coupled onto a few-mode (including single-mode) optical fiber. Different arrangements and applications for such optical mode field converters are disclosed in U.S. Provisional Patent Application Serial No. 61/651,771, filed on May 25, 2012, the entire content of which is incorporated herein by reference as if set forth in its entirety. The techniques disclosed herein may be used to form the various light focusing elements disclosed in U.S. Provisional Patent Application Serial No. 61/651,771.

[0086] Pursuant to embodiments of the present invention, methods of fabricating light focusing elements are provided that may be used to inexpensively mass-produce light focusing elements for fiber optic communications systems. In particular, hundreds or thousands of light focusing elements may be formed in or on a single substrate, and this substrate may then be diced to provide hundreds or thousands of individual light focusing elements. In addition, many of the light focusing elements according to embodiments of the present invention may be designed to receive light in a direction that is generally perpendicular to a top surface of the substrate (typically the substrate will be a disk-like element that has a large top surface, a large bottom surface, and side surface(s) that are much smaller than the top and bottom surfaces).

[0087] Embodiments of the present invention have been described above with reference to the accompanying drawings, in which embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth above. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

[0088] It will be understood that, although the terms first, second, etc. may be used above and in the claims that follow to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present invention. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0089] It will be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present. Other words used to describe the relationship between elements should be interpreted in a like fashion (*i.e.*, "between" versus "directly between", "adjacent" versus "directly adjacent", etc.).

[0090] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" "comprising," "includes" and/or "including" when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0091] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this disclosure and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0092] All embodiments can be combined in any way and/or combination.

[0093] Many variations and modifications can be made to the preferred embodiments without substantially departing from the principles of the present invention. All such variations and modifications are intended to be included herein within the scope of the present invention, as set forth in the following claims.

That Which is Claimed is:

1. A method of fabricating light focusing elements for use in a fiber optic communications system, comprising:

forming a plurality of light focusing elements on or in a top surface of a substrate;

dicing the substrate to singulate the light focusing elements.

2. The method of Claim 1, wherein each light focusing element is configured to focus a large area light field that is incident in a direction that is generally normal to the top surface of the substrate into a smaller area light field.

3. The method of Claim 2, wherein the light focusing elements comprise graded index structures, graded index waveguides or Fresnel lenses.

4. The method of Claim 1, wherein the substrate comprises a transparent substrate for light at wavelengths in the range from about 830 nanometers to about 1360 nanometers.

5. The method of Claim 1, further comprising at least partly removing a bottom surface of the substrate after forming the plurality of light focusing elements thereon.

6. The method of Claim 1, wherein the light focusing elements are formed using photolithography processes to etch the top surface of the substrate or one or more layers that are deposited on the top surface of the substrate.

7. The method of Claim 6, wherein the photolithography process includes:

depositing a photoresist on a top surface of the substrate;

using a photomask to transfer a geometric pattern onto the photoresist, the geometric pattern comprising a plurality of openings in the photoresist that expose the substrate; and

etching the exposed portions of the substrate using the photoresist as an etching mask.

8. The method of Claim 1, wherein the light focusing elements are formed via laser micro-machining.

9. The method of Claim 1, wherein the light focusing elements are formed via a two-photon polymerization process, which process includes the steps of:

depositing a gel on the substrate;

inducing a chemical reaction in selected portions of the gel to cross-link the selected portions of the gel; and

draining away non-cross-linked portions of the gel from the substrate.

10. The method of Claim 1, wherein forming the plurality of light focusing elements on or in the top surface of the substrate comprises:

growing one or more material layers on the top surface of the substrate; and

patterning the grown material layers to form the plurality of light focusing elements.

11. The method of Claim 1, wherein forming the plurality of light focusing elements on or in the top surface of the substrate comprises:

selectively growing the light focusing elements on the top surface of the substrate.

12. A wafer, comprising:

a substrate;

a plurality of light focusing elements on an upper surface of the substrate;

a plurality of scribe lines that separate the light focusing elements into rows and columns,

wherein each light focusing element is configured to focus a large area light field that is incident in a direction that is generally normal to the top surface of the substrate into a smaller area light field.

13. The wafer of Claim 12, wherein the light focusing elements comprise graded index structures, graded index waveguides or Fresnel lenses.

14. The wafer of Claim 12, wherein the substrate comprises a transparent substrate for light at wavelengths in the range from about 830 nanometers to about 1360 nanometers.

15. A method of fabricating light focusing elements for use in a fiber optic communications system, comprising:

forming a plurality of diffractive patterns on a substrate via at least one of lithography, dry etching, wet etching, laser micromachining or nano-machining to form a plurality of light focusing elements on the substrate;

dicing the substrate to singulate the light focusing elements.

16. The method of Claim 15, wherein each light focusing element is configured to focus a large area light field that is incident in a direction that is generally normal to the top surface of the substrate into a smaller area light field.

17. The method of Claim 15, wherein the light focusing elements are formed using photolithography processes to etch a top surface of the substrate or one or more layers that are deposited on the top surface of the substrate.

18. The method of Claim 15, wherein the light focusing elements comprise graded index structures, graded index waveguides or Fresnel lenses.

19. The method of Claim 2, wherein the light focusing elements comprise diffractive structures that include a plurality if different shaped and sized islands of material extending upwardly from the substrate.

20. The method of Claim 2, wherein the light focusing elements comprise binary Fresnel lenses.

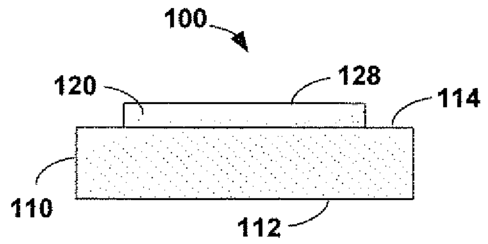

FIG. 1A

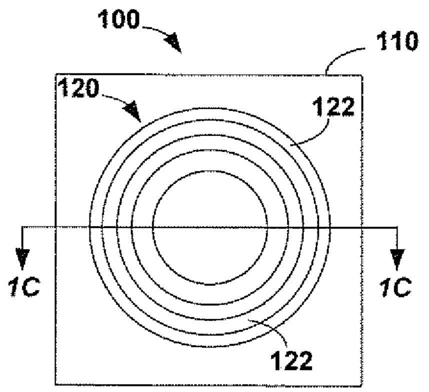

FIG. 1B

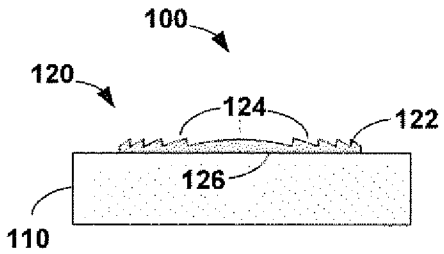

FIG. 1C

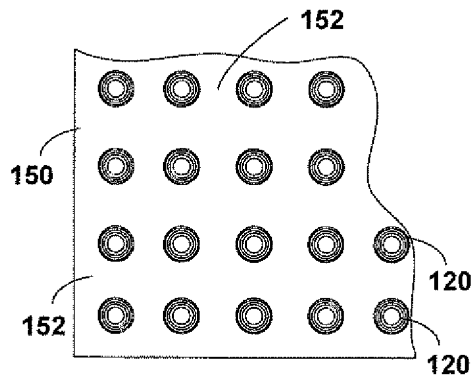

FIG. 1D

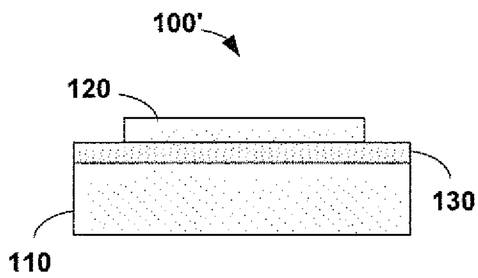

FIG. 1E

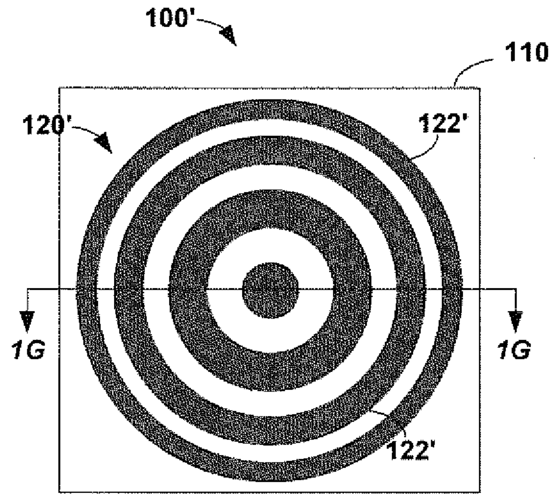

FIG. 1F

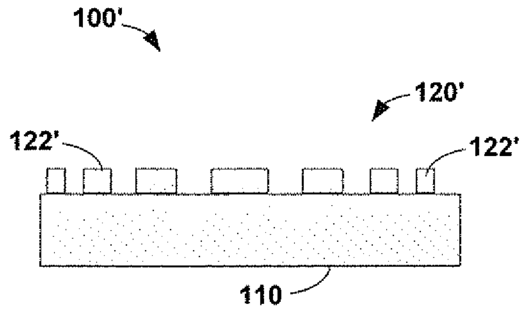

FIG. 1G

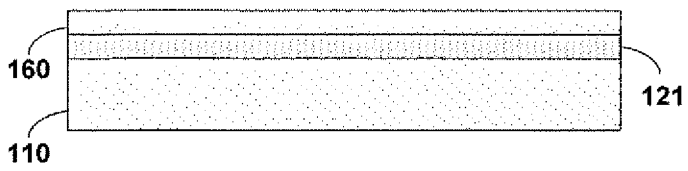

FIG. 2A

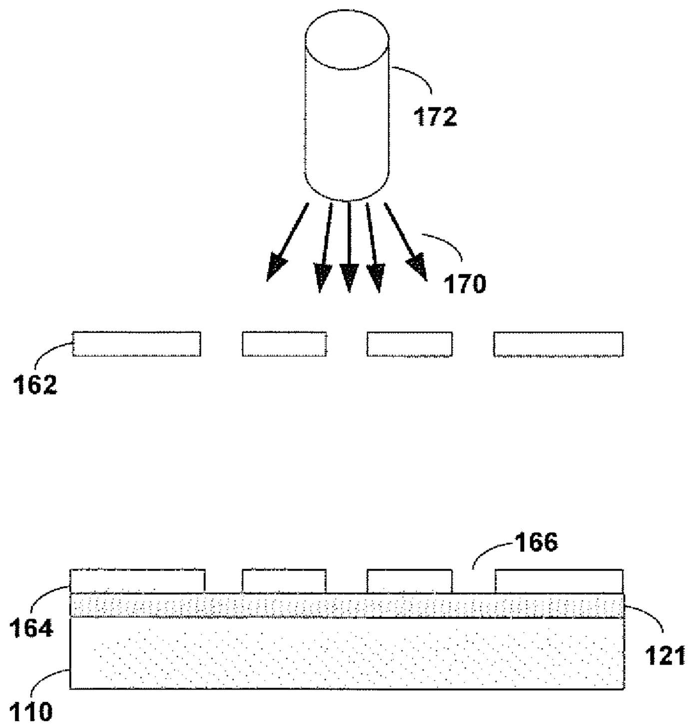

FIG. 2B

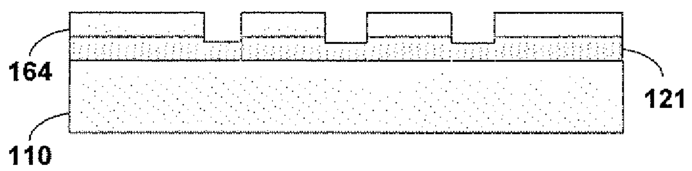

FIG. 2C

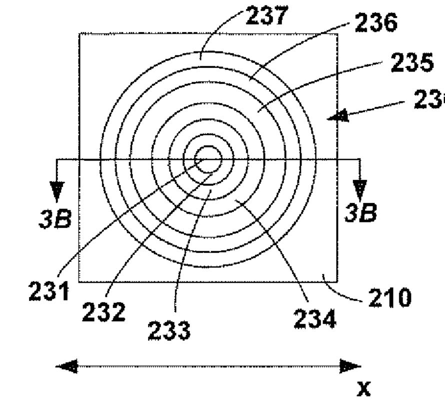

FIG. 3A

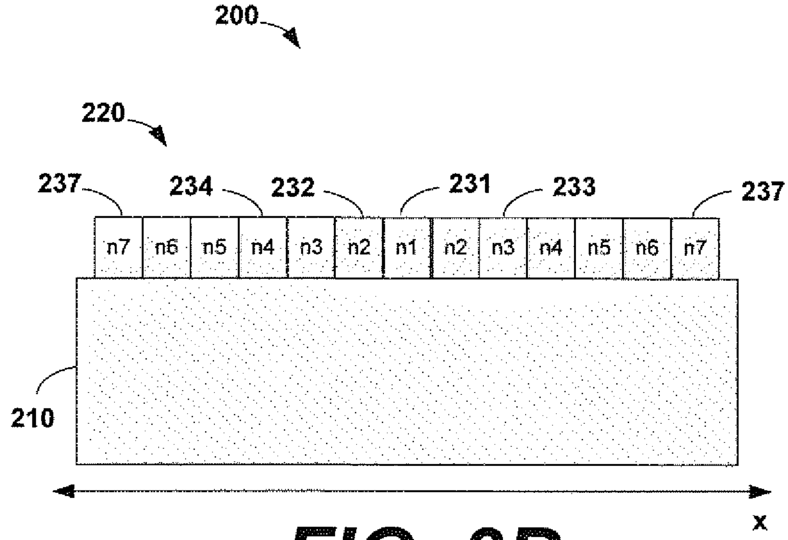

FIG. 3B

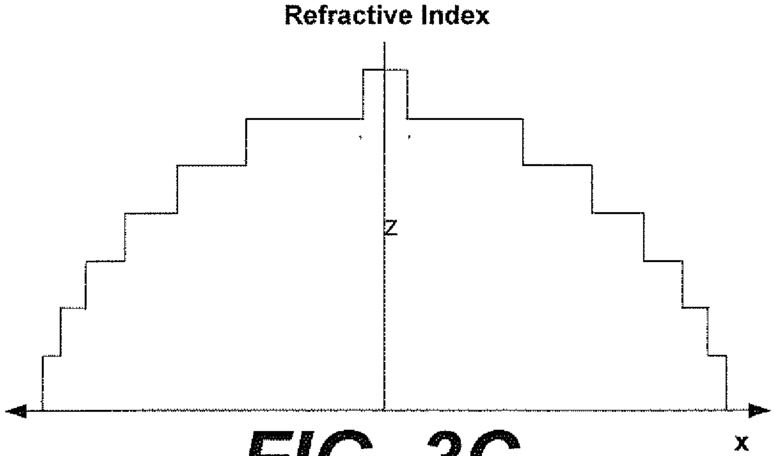

FIG. 3C

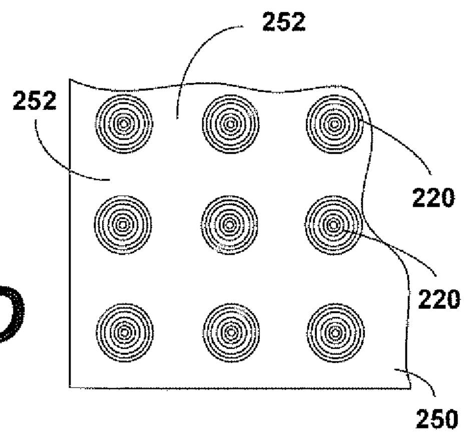

FIG. 3D

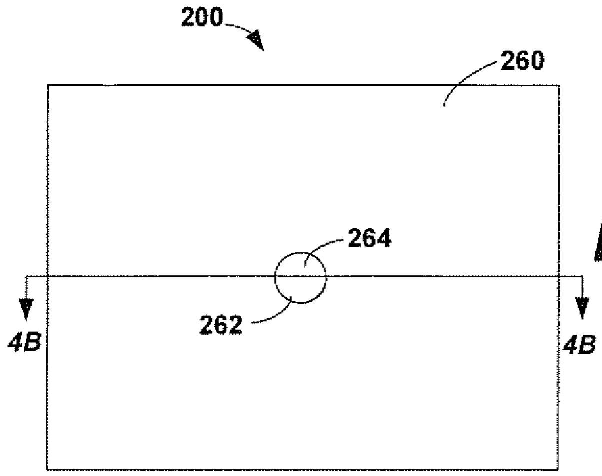

FIG. 4A

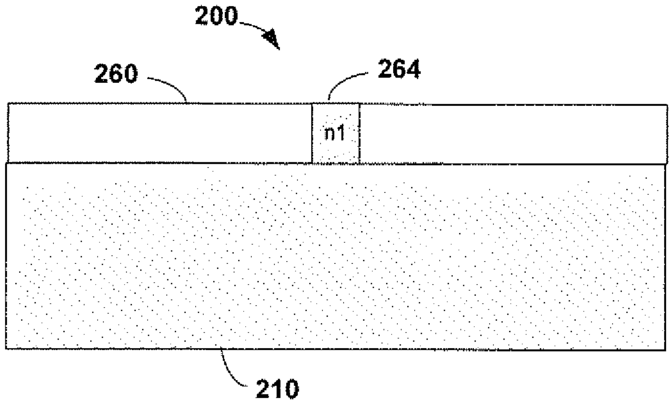

FIG. 4B

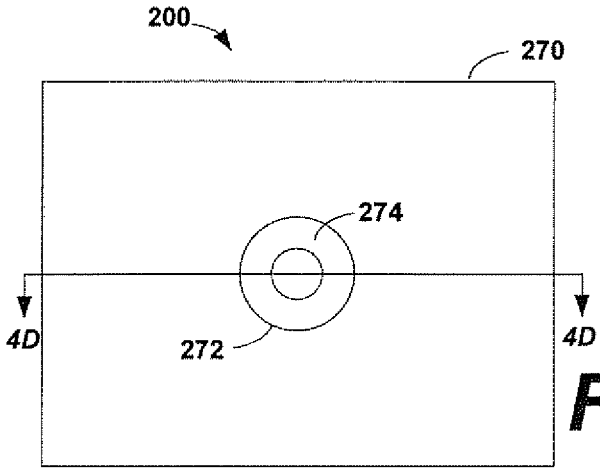

FIG. 4C

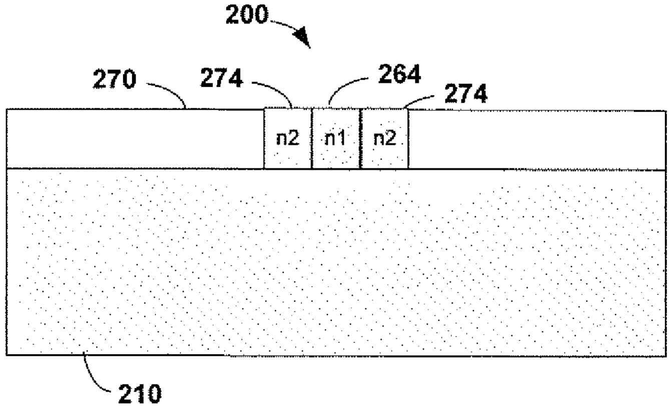

FIG. 4D

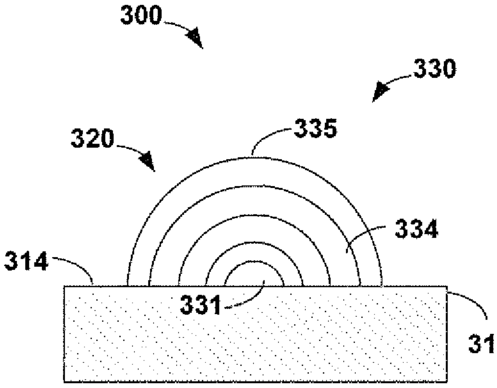

FIG. 5A

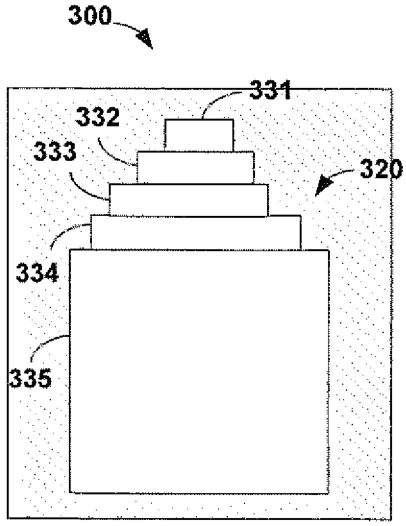

FIG. 5B

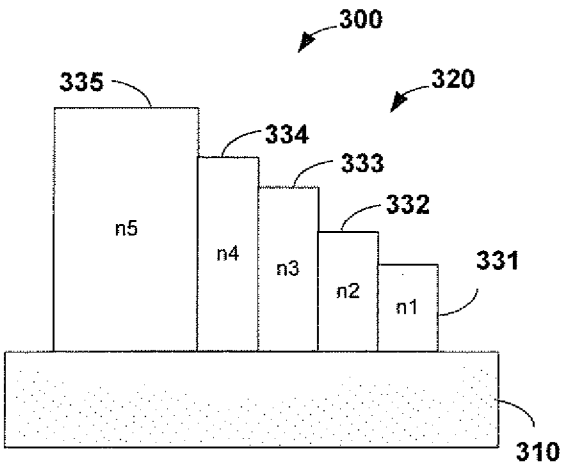

FIG. 5C

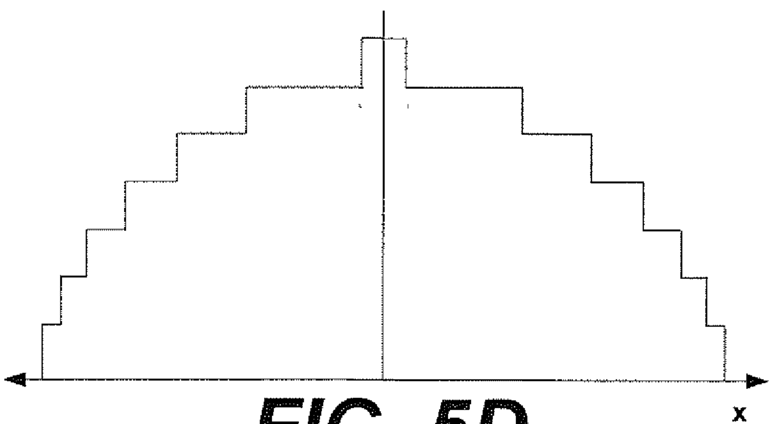

FIG. 5D

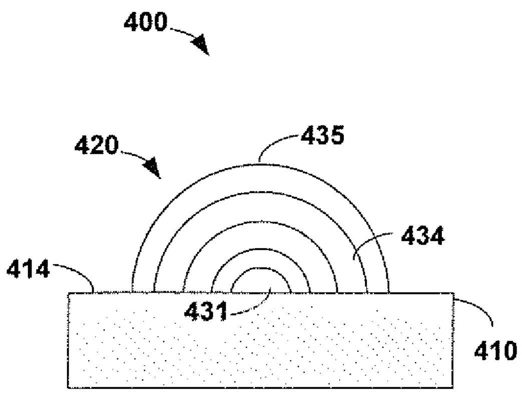

FIG. 6A

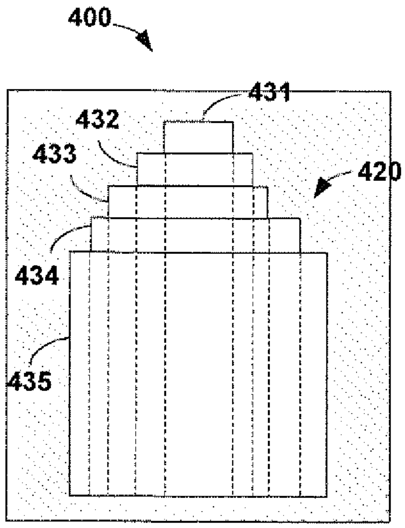

FIG. 6B

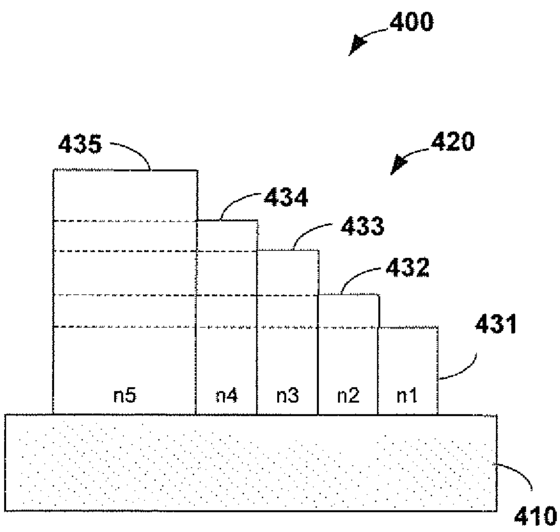

FIG. 6C

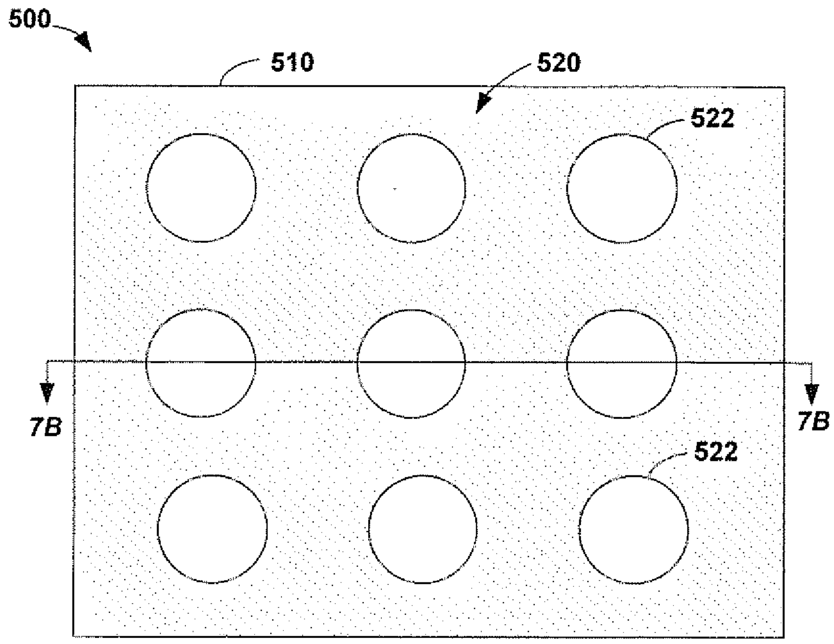

FIG. 7A

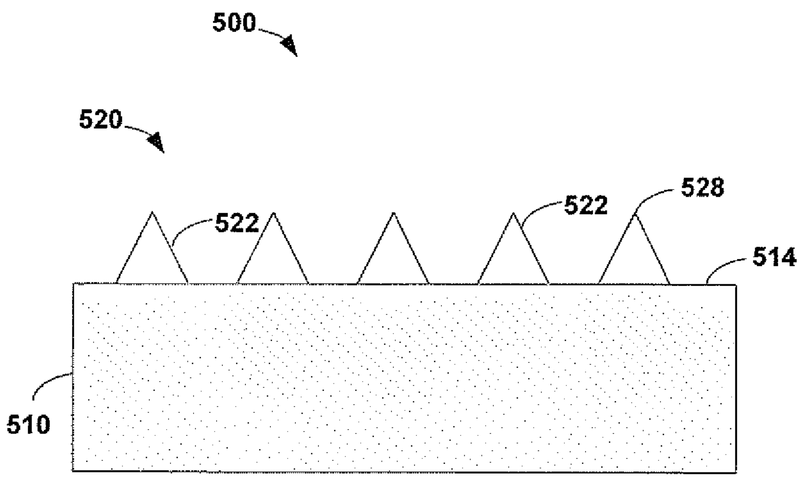

FIG. 7B

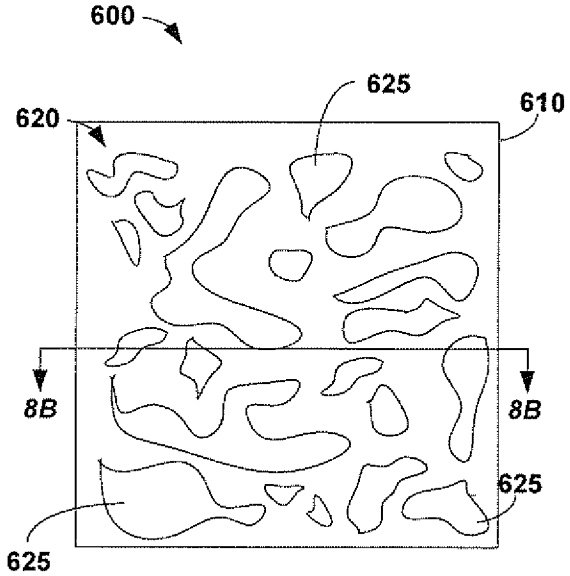

FIG. 8A

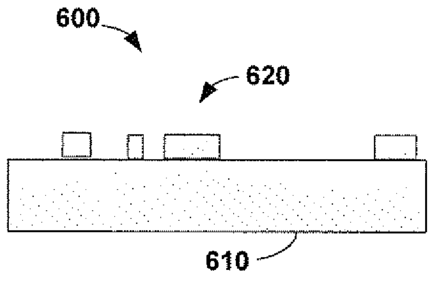

FIG. 8B

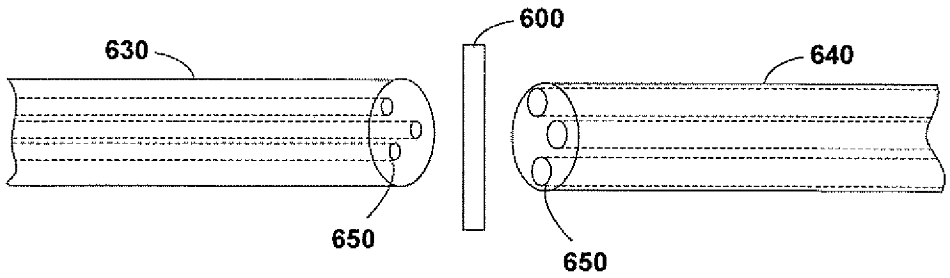

FIG. 8C

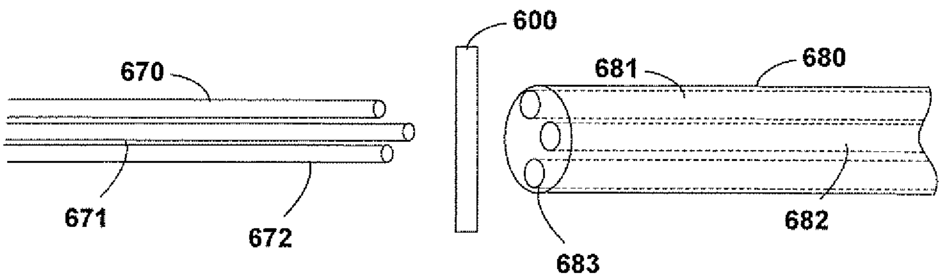

FIG. 8D

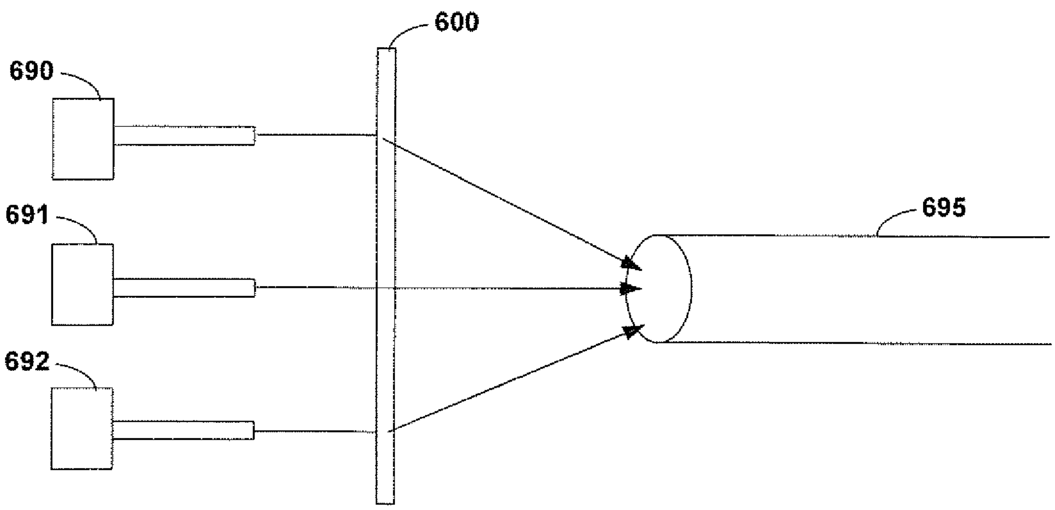

FIG. 8E

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/047753

A. CLASSIFICATION OF SUBJECT MATTER

G02B 6/125(2006.01)i, G02B 6/32(2006.01)i, G02B 6/00(2006.01)i, H04B 10/25(2013.01)i

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 6/125; G02B 27/10; G02B 3/08; C23F 1/00; G02B 3/00; B29D 11/00; H01L 27/14; G02B 6/32; G02B 6/00; H04B 10/25

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: Fresnel lens, wafer, dicing, mask, resist

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4609259 A (SUEMITSU et al.) 02 September 1986 See columns 1, 4, claim 1 and figures 1-3, 6, 9.	1-20
Y	US 8072685 B1 (WU et al.) 06 December 2011 See column 1, claim 1 and figure 5.	1-20
A	WO 2007-100933 A2 (KLA TENCOR TECHNOLOGIES CORP.) 07 September 2007 See abstract, claims 66-67 and figure 11A.	1-20
A	JP 2008-039831 A (DAINIPPON PRINTING CO., LTD.) 21 February 2008 See abstract, claim 1 and figure 1.	1-20
A	KR 10-2011-0092138 A (SEKONIX CO., LTD.) 17 August 2011 See abstract, claim 1 and figures 1-2.	1-20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of 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
26 September 2013 (26.09.2013)	**26 September 2013 (26.09.2013)**

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2013/047753

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		TW 201231258 A	01/08/2012
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		US 8052885 B2	08/11/2011
		WO 2007-100933 A3	10/04/2008
JP 2008-039831 A	21/02/2008	None	
KR 10-2011-0092138 A	17/08/2011	None	