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(54) Title: LASER PROCESSING OF SLOTS AND HOLES

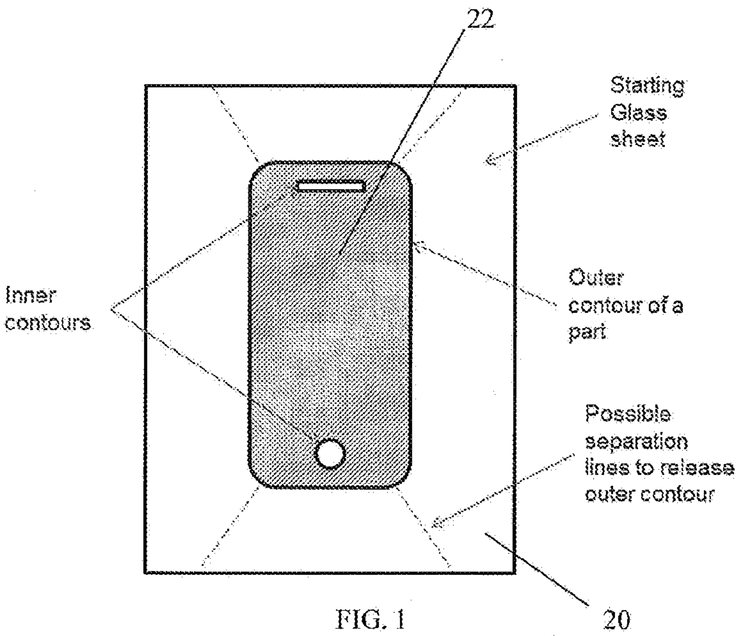

FIG. 1

(57) **Abstract**: The present invention relates to a process for cutting and separating interior contours in thin substrates of transparent materials, in particular glass. The method involves the utilization of an ultra-short pulse laser to form perforation or holes in the substrate, that may be followed by use of a CO_2 laser beam to promote full separation about the perforated line.

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LASER PROCESSING OF SLOTS AND HOLES

RELATED APPLICATION(S)

[0001] This application claims the benefit of priority under 35 U.S.C. § 120 of U.S. Application Serial No. 14/536009 filed on November 7, 2014 which claims the benefit of U.S. Provisional Application No. 61/917148 filed on December 17, 2013 and U.S. Provisional Application No. 62/022855 filed on July 10, 2014. The entire teachings of these applications are incorporated herein by reference.

BACKGROUND

[0002] The cutting of holes and slots in thin substrates of transparent materials, such as glass, can be accomplished by focused laser beams that are used to ablate material along the contour of a hole or slot, where multiple passes are used to remove layer after layer of material until the inner plug no longer is attached to the outer substrate piece. The problem with such processes is that they require many passes (dozens or even more) of the laser beam to remove the material layer by layer, they generate significant ablative debris which will contaminate the surfaces of the part, and they generate a lot of subsurface damage (>100 μm) along the edge of the contour.

[0003] Therefore, there is a need for an improved process for cutting holes and slots.

SUMMARY

[0004] Embodiments described herein relate to a process for cutting and separating interior contours in thin substrates of transparent materials, in particular glass.

[0005] In one embodiment, a method of laser drilling a material includes focusing a pulsed laser beam into a laser beam focal line, viewed along the beam propagation direction, directing the laser beam focal line into the material at a first

location, the laser beam focal line generating an induced absorption within the material, the induced absorption producing a hole along the laser beam focal line within the material, translating the material and the pulsed laser beam relative to each other starting from the first location along a first closed contour, thereby laser drilling a plurality of holes along the first closed contour within the material, translating the material and the pulsed laser beam relative to each other starting from the first location along a first closed contour, thereby laser drilling a plurality of holes along the first closed contour within the material, and directing a carbon dioxide (CO2) laser into the material around a second closed contour contained within the first closed contour to facilitate removal of an inner plug of the material along the first closed contour.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0007] The foregoing will be apparent from the following more particular description of example embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating embodiments of the present invention.

[0008] FIG. 1 is an illustration of a part to be cut out of a starting sheet. The part has both outer and inner contours. The outer contour can be easily released from the mother sheet by adding in additional cuts or “release lines.”

[0009] FIGS. 2A and 2B are illustrations of positioning of the laser beam focal line, i.e., the processing of a material transparent for the laser wavelength due to the induced absorption along the focal line.

[0010] FIG. 3A is an illustration of an optical assembly for laser drilling.

[0011] FIG. 3B-1 thru 3B-4 is an illustration of various possibilities to process the substrate by differently positioning the laser beam focal line relative to the substrate.

[0012] FIG. 4 is an illustration of a second optical assembly for laser drilling.

[0013] FIGS. 5A and 5B are illustrations of a third optical assembly for laser drilling.

[0014] FIG. 6 is a schematic illustration of a fourth optical assembly for laser drilling.

[0015] FIG. 7A-7C is an illustration of different regimes for laser processing of materials. FIG. 7A illustrates an unfocused laser beam, FIG. 7B illustrates a condensed laser beam with a spherical lens, and FIG. 7C illustrates a condensed laser beam with an axicon or diffractive Fresnel lens.

[0016] FIG. 8A illustrates schematically the relative intensity of laser pulses within an exemplary pulse burst vs. time, with each exemplary pulse burst having 3 pulses.

[0017] FIG. 8B illustrates schematically relative intensity of laser pulses vs. time within an exemplary pulse burst, with each exemplary pulse burst containing 5 pulses.

[0018] FIG. 8C is a description of different laser steps and paths traced out to define an inner contour and remove the material inside this contour.

[0019] FIG. 9 is a description of the CO_2 laser step and path traced out to remove the material inside the contour.

[0020] FIG. 10 is an example of a hole and slot cut and then separated from a 0.7 mm thick sample. The hole and slot were cut and removed using the process according to this invention.

[0021] FIG. 11 is an angled image of the interior edge of a slot formed with the process described herein, after the CO_2 ablation process has been used to remove the interior material.

[0022] FIG. 12 is an edge image of a straight cut strip of 0.7 mm thick Corning 2320 NIOX (not ion exchanged) thick substrate, an exterior contour. This edge can be compared to the very similar edge shown in FIG. 11.

[0023] FIG. 13 is a top view of a cut edge of a slot made with the process described herein. No chipping or checking is observed on the edge of the contour. This contour has a radius of about 2 mm.

[0024] FIGS. 14A-14C are illustrations of a fault line (or perforated line) with equally spaced defect lines or damage tracks of modified glass.

DETAILED DESCRIPTION

[0025] A description of example embodiments follows.

[0026] Disclosed herein is a process for cutting and separating interior contours in thin substrates of transparent materials, in particular glass. The method involves the utilization of an ultra-short pulse laser to form perforation or holes in the substrate, that may be followed by use of a CO_2 laser beam to promote full separation about the perforated line. The laser process described below generates full body cuts of a variety of glasses in a single pass, with low sub-surface damage (<75um), and excellent surface roughness (Ra<0.5um). Sub-surface damage (SSD) is defined as the extent of cracks or "checks" perpendicular to the cut edge of the glass piece. The magnitude of the distance these cracks extend into the glass piece can determine the amount of later material removal that may be needed from grinding and polishing operations that are used to improve glass edge strength. SSD may be measured by using confocal microscope to observed light scattering from the cracks, and determining the maximum distance the cracks extend into the body of the glass over a given cut edge.

[0027] One embodiment relates a method to cut and separate interior contours in materials such as glass, with a separation process that exposes the high quality edge generated by the above-mentioned perforation process without damaging it by the separation process. When a part is cut out of a starting sheet of substrate, it may be comprised of outer or inner contours, as shown in FIG. 1. Release of outer contour the part from the sheet can be done by adding additional cut lines known as "release lines", as shown in FIG. 1. However, for the interior contours, no release lines can be made, as they would mar the part of interest. In some cases, for the highly stressed materials and large enough interior contours, the inner part may self-separate and fall out. However, for small holes and slots (e.g., 10 mm holes, slots of widths <few mm, for example ≤3 mm, or ≤2 mm, or even ≤1 mm), even for stressed materials, the inner part will not fall out. A hole is generally defined as a circular, or substantially circular feature in crossection. In contrast, slots are generally have highly elliptical features, such as features that have aspect ratios (e.g., cross-sectional or as viewed from the top or bottom, for example) of length to width of

>4:1, typically ≥5:1, for example 1.5 mm x 15 mm, or 3 mm x 15 mm, or 1 mm x 10 mm, or 1.5 mm by 7 mm, etc. Slots may have radiused corners, or the corners may be sharp (90 degree) features.

[0028] The challenge with separating an interior contour, such as a hole in a glass piece required for the "home" or power button on a smart phone, is that even if the contour is well perforated and a crack propagates around it, the inner plug of material may be under compressive pressure and locked in place by the material surrounding the plug. This means that the challenging part is an automated release process that allows the plug to drop out. This problem occurs regardless of whether or not the material to be cut is high stress and easy to form cracks in, like in the case of a chemically strengthened glass substrate like Gorilla® Glass, or if the material is low stress, like in the case of Eagle XG® glass. A high stress glass is a glass having central (in the center of the thickness of the glass) tension greater than about 24 MPa; while a low stress glass typically has a central tension less than about 24 MPa.

[0029] The present application is generally directed to a laser method and apparatus for precision cutting and separation of arbitrary shapes out of glass substrates in a controllable fashion, with negligible debris and minimum damage to part edges that preserves strength. The developed laser method relies on the material transparency to the laser wavelength in linear regime, or low laser intensity, which allows maintenance of a clean and pristine surface quality and on the reduced subsurface damage created by the area of high intensity around the laser focus. One of the key enablers of this process is the high aspect ratio of the defect created by the ultra-short pulsed laser. It allows creation of a fault line that extends from the top to the bottom surfaces of the material to be cut. In principle, this defect can be created by a single laser pulse and if necessary, additional pulses can be used to increase the extension of the affected area (depth and width).

[0030] Using a short pulse picosecond laser and optics which generate a focal line, a closed contour is perforated in a glass sheet. The perforations are less than a few microns in diameter, typical spacing of the perforations is 1-15 μm, and the perforations go entirely through the glass sheet.

[0031] To generate a weak point to facilitate material removal, an additional contour could then be optionally perforated with the same process a few hundred microns to the interior of the first contour.

[0032] A focused CO_2 laser beam, of a high enough power density to ablate the glass material, is then traced around the second contour, causing the glass material to fragment and be removed. One or more passes of the laser may be used. A high pressure assist gas is also forced out through a nozzle collinearly to the CO_2 beam, to provide additional force to drive the glass material out of the larger glass piece.

[0033] The method to cut and separate transparent materials is essentially based on creating a fault line on the material to be processed with an ultra-short pulsed laser. Depending on the material properties (absorption, CTE, stress, composition, etc.) and laser parameters chosen for processing that determined material, the creation of a fault line alone can be enough to induce self-separation. This is the case for most strengthened glasses (those that have already undergone ion-exchange before cutting) that have significant (i.e., greater than about 24 MPa) internal or central tension (CT). In this case, no secondary separation processes, such as tension/bending forces or CO_2 laser, are necessary.

[0034] In some cases, the created fault line is not enough to separate the glass automatically. This is often the case for display glasses such as Eagle XG®, Lotus, or ion-exchangeable glasses that are cut before any ion-exchange step. Thus, a secondary process step may be necessary. If so desired, a second laser can be used to create thermal stress to separate it, for example. In the case of Corning code 2320 NIOX (non-ion exchanged Gorilla® Glass 3), we have found that separation can be achieved, after the creation of a defect line, by application of mechanical force or by tracing the existing fault line with an infrared CO_2 laser beam to create thermal stress and force the parts to self-separate. Another option is to have the CO_2 laser only start the separation and finish the separation manually. The optional CO_2 laser separation is achieved with a defocused (i.e. spot size at the glass of 2-12 mm in diameter) continuous wave laser emitting at 10.6 μm and with power adjusted by controlling its duty cycle. Focus change (i.e., extent of defocusing) is used to vary the induced thermal stress by varying the spot size. After generation of the perforation lines, CO_2 induced separation can generally be achieved by using a power at the glass of ~40W, a spot size of about 2 mm, and a traverse rate of the beam of ~14-20 m/minute.

[0035] However, even if the glass has enough internal stress to start self-separation after the formation of the defect line, the geometry of the cut contour may prevent an interior glass part from releasing. This is the case for most closed or inner contours, such as simple holes or slots. The interior portion of the aperture will remain in place due to the compression forces present in the glass sheet – the cracks may propagate between the perforated defects, but no room exists to allow the piece to fall out of the mother sheet.

Forming the defect or perforation line

[0036] For the first process step, there are several methods to create that defect line. The optical method of forming the line focus can take multiple forms, using donut shaped laser beams and spherical lenses, axicon lenses, diffractive elements, or other methods to form the linear region of high intensity. The type of laser (picosecond, femtosecond, etc.) and wavelength (IR, green, UV, etc.) can also be varied, as long as sufficient optical intensities are reached to create breakdown of the substrate material. This wavelength may be, for example, 1064, 532, 355 or 266 nanometers.

[0037] Ultra-short pulse lasers can be used in combination with optics that generate a focal line to fully perforate the body of a range of glass compositions. In some embodiments, the pulse duration of the individual pulses is in a range of between greater than about 1 picoseconds and less than about 100 picoseconds, such as greater than about 5 picoseconds and less than about 20 picoseconds, and the repetition rate of the individual pulses can be in a range of between about 1 kHz and 4 MHz, such as in a range of between about 10 kHz and 650 kHz.

[0038] In addition to a single pulse operation at the aforementioned individual pulse repetition rates, the pulses can be produced in bursts of two pulses, or more (such as, for example, 3 pulses, 4, pulses, 5 pulses, 10 pulses, 15 pulses, 20 pulses, or more) separated by a duration between the individual pulses within the pulse burst that is in a range of between about 1 nsec and about 50 nsec, for example, 10-50 nsec, or 10 to 30 nsec, such as about 20 nsec, and the burst repetition frequency can be in a range of between about 1 kHz and about 200 kHz. (Bursting or producing pulse bursts is a type of laser operation where the emission of pulses is not in a uniform and steady stream but rather in tight clusters of pulses.) The pulse burst laser beam can have a wavelength selected such that the material is substantially transparent at this wavelength. The average laser power per burst measured at the material can be greater than 40 microJoules per mm thickness of material, for example between 40 microJoules/mm and 2500 microJoules/mm, or between 200 and 800 microJoules/mm. For example, for 0.5mm-0.7 mm thick Corning 2320 non-ion exchanged glass one may use 200 μJ pulse bursts to cut and separate the glass, which gives an exemplary range of 285-400 μJ/mm. The glass is moved relative to the laser beam (or the laser beam is translated relative to the glass) to create perforated lines that trace out the shape of any desired parts.

[0039] The laser creates hole-like defect zones (or damage tracks, or defect lines) that penetrate the full depth the glass, with internal openings, for example of approximately 1 micron in diameter. These perforations, defect regions, damage tracks, or defect lines are generally spaced from 1 to 15 microns apart (for example, 2-12 microns, or 3-10 microns). The defect lines extend, for example, through the thickness of the glass sheet, and are orthogonal to the major (flat) surfaces of the glass sheet.

[0040] In one embodiment, an ultra-short (~10 psec) burst pulsed laser is used to create this high aspect ratio vertical defect line in a consistent, controllable and repeatable manner. The detail of the optical setup that enables the creation of this vertical defect line is described below and in U.S. Application No. 61/752,489, filed on January 15, 2013. The essence of this concept is to use an axicon lens element in an optical lens assembly to create a region of high aspect ratio taper-free microchannel using ultra-short (picoseconds or femtosecond duration) Bessel beams. In other words, the axicon condenses the laser beam into a region of cylindrical shape and high aspect ratio (long length and small diameter). Due to the high intensity created with the condensed laser beam, nonlinear interaction of the laser electromagnetic field and the material occurs and the laser energy is transferred to the substrate. However, it is important to realize that in the areas where the laser energy intensity is not high (i.e., glass surface, glass volume surrounding the central convergence line), nothing happens to the glass as the laser intensity is below the nonlinear threshold.

[0041] Turning to FIGS. 2A and 2B, a method of laser drilling a material includes focusing a pulsed laser beam 2 into a laser beam focal line 2b, viewed along the beam propagation direction. As shown in FIG. 3, laser 3 (not shown) emits laser beam 2, at the beam incidence side of the optical assembly 6 referred to as 2a, which is incident on the optical assembly 6. The optical assembly 6 turns the incident laser beam into an extensive laser beam focal line 2b on the output side over a defined expansion range along the beam direction (length l of the focal line). The planar substrate 1 to be processed is positioned in the beam path after the optical assembly overlapping at least partially the laser beam focal line 2b of laser beam 2. Reference 1a designates the surface of the planar substrate facing the optical assembly 6 or the laser, respectively, reference 1b designates the reverse surface of substrate 1 usually spaced in parallel. The substrate thickness (measured perpendicularly to the planes 1a and 1b, i.e., to the substrate plane) is labeled with d.

[0042] As FIG. 2A depicts, substrate 1 is aligned perpendicularly to the longitudinal beam axis and thus behind the same focal line 2b produced by the optical assembly 6 (the substrate is perpendicular to the drawing plane) and viewed along the beam direction it is positioned relative to the focal line 2b in such a way that the focal line 2b viewed in beam direction starts before the surface 1a of the substrate and stops before the surface 1b of the substrate, i.e. still within the substrate. In the overlapping area of the laser beam focal line 2b with substrate 1, i.e. in the substrate material covered by focal line 2b, the extensive laser beam focal line 2b thus generates (in case of a suitable laser intensity along the laser beam focal line 2 b which is ensured due to the focusing of laser beam 2 on a section of length l, i.e. a line focus of length l) an extensive section 2c viewed along the longitudinal beam direction, along which an induced absorption is generated in the substrate material which induces a defect line or crack formation in the substrate material along section 2c. The crack formation is not only local, but over the entire length of the extensive section 2c of the induced absorption. The length of section 2c (i.e., after all, the length of the overlapping of laser beam focal line 2b with substrate 1) is labeled with reference L. The average diameter or the average extension of the section of the induced absorption (or the sections in the material of substrate 1 undergoing the crack formation) is labeled with reference D. This average extension D basically corresponds to the average diameter δ of the laser beam focal line 2b, that is, an average spot diameter in a range of between about 0.1 μm and about 5 μm.

[0043] As FIG. 2A shows, substrate material transparent for the wavelength λ of laser beam 2 is heated due to the induced absorption along the focal line 2b. FIG. 2B outlines that the warming material will eventually expand so that a correspondingly induced tension leads to micro-crack formation, with the tension being the highest at surface 1a.

[0044] Concrete optical assemblies 6, which can be applied to generate the focal line 2b, as well as a concrete optical setup, in which these optical assemblies can be applied, are described below. All assemblies or setups are based on the description above so that identical references are used for identical components or features or those which are equal in their function. Therefore only the differences are described below.

[0045] As the parting face eventually resulting in the separation is or must be of high quality (regarding breaking strength, geometric precision, roughness and avoidance of re-machining requirements), the individual focal lines to be positioned on the substrate surface along parting line 5 should be generated using the optical assembly described below (hereinafter, the optical assembly is alternatively also referred to as laser optics). The roughness results particularly from the spot size or the spot diameter of the focal line. In order to achieve a low spot size of, for example, 0.5 μm to 2 μm in case of a given wavelength λ of laser 3 (interaction with the material of substrate 1), certain requirements must usually be imposed on the numerical aperture of laser optics 6. These requirements are met by laser optics 6 described below.

[0046] In order to achieve the required numerical aperture, the optics must, on the one hand, dispose of the required opening for a given focal length, according to the known Abbé formulae (N.A. = n sin (theta), n: refractive index of the glass to be processes, theta: half the aperture angle; and theta = arctan (D/2f); D: aperture, f: focal length). On the other hand, the laser beam must illuminate the optics up to the required aperture, which is typically achieved by means of beam widening using widening telescopes between laser and focusing optics.

[0047] The spot size should not vary too strongly for the purpose of a uniform interaction along the focal line. This can, for example, be ensured (see the embodiment below) by illuminating the focusing optics only in a small, circular area so that the beam opening and thus the percentage of the numerical aperture only vary slightly.

[0048] According to FIG. 3A (section perpendicular to the substrate plane at the level of the central beam in the laser beam bundle of laser radiation 2; here, too, the center of the laser beam 2 is preferably perpendicularly incident to the substrate plane, i.e. angle is 0° so that the focal line 2b or the extensive section of the induced absorption 2c is parallel to the substrate normal), the laser radiation 2a emitted by laser 3 is first directed onto a circular aperture 8 which is completely opaque for the laser radiation used. Aperture 8 is oriented perpendicular to the longitudinal beam axis and is centered on the central beam of the depicted beam bundle 2a. The diameter of aperture 8 is selected in such a way that the beam bundles near the center of beam bundle 2a or the central beam (here labeled with 2aZ) hit the aperture and are completely absorbed by it. Only the beams in the outer perimeter range of beam bundle 2a (marginal rays, here labeled with 2aR) are not absorbed due to the reduced aperture size compared to the beam diameter, but pass aperture 8 laterally and hit the marginal areas of the focusing optic elements of the optical assembly 6, which is designed as a spherically cut, bi-convex lens 7 here.

[0049] Lens 7 centered on the central beam is deliberately designed as a non-corrected, bi-convex focusing lens in the form of a common, spherically cut lens. Put another way, the spherical aberration of such a lens is deliberately used. As an alternative, aspheres or multi-lens systems deviating from ideally corrected systems, which do not form an ideal focal point but a distinct, elongated focal line of a defined length, can also be used (i.e., lenses or systems which do not have a single focal point). The zones of the lens thus focus along a focal line 2b, subject to the distance from the lens center. The diameter of aperture 8 across the beam direction is approximately 90 % of the diameter of the beam bundle (beam bundle diameter defined by the extension to the decrease to $1/e^2$) (intensity) and approximately 75 %

of the diameter of the lens of the optical assembly 6. The focal line 2b of a non-aberration-corrected spherical lens 7 generated by blocking out the beam bundles in the center is thus used. FIG. 3A shows the section in one plane through the central beam, the complete three-dimensional bundle can be seen when the depicted beams are rotated around the focal line 2b.

[0050] One disadvantage of this focal line is that the conditions (spot size, laser intensity) along the focal line, and thus along the desired depth in the material, vary and therefore the desired type of interaction (no melting, induced absorption, thermal-plastic deformation up to crack formation) may possibly only be selected in a part of the focal line. This means in turn that possibly only a part of the incident laser light is absorbed in the desired way. In this way, the efficiency of the process (required average laser power for the desired separation speed) is impaired on the one hand, and on the other hand the laser light might be transmitted into undesired deeper places (parts or layers adherent to the substrate or the substrate holding fixture) and interact there in an undesirable way (heating, diffusion, absorption, unwanted modification).

[0051] FIG. 3B-1-4 show (not only for the optical assembly in FIG. 3A, but basically also for any other applicable optical assembly 6) that the laser beam focal line 2b can be positioned differently by suitably positioning and/or aligning the optical assembly 6 relative to substrate 1 as well as by suitably selecting the parameters of the optical assembly 6: As FIG. 3B-1 outlines, the length l of the focal line 2b can be adjusted in such a way that it exceeds the substrate thickness d (here by factor 2). If substrate 1 is placed (viewed in longitudinal beam direction) centrally to focal line 2b, an extensive section of induced absorption 2c is generated over the entire substrate thickness.

[0052] In the case shown in FIG. 3B-2, a focal line 2b is generated which has a length l which is substantially the same as the substrate thickness d. As substrate 1 relative to line 2 is positioned in such a way that line 2b starts in a point before, i.e. outside the substrate, the length L of the extensive section of induced absorption 2c (which extends here from the substrate surface to a defined substrate depth, but not to the reverse surface 1b) is smaller than the length l of focal line 2b. FIG. 3B-3 shows the case in which the substrate 1 (viewed along the beam direction) is partially positioned before the starting point of focal line 2b so that, here too, it applies to the length l of line 2b l > L (L = extension of the section of induced absorption 2c in substrate 1). The focal line thus starts within the substrate and extends over the reverse surface 1b to beyond the substrate. FIG. 3B-4 finally shows the case in which the generate focal line length l is smaller than the substrate thickness d so that - in case of a central positioning of the substrate relative to the focal line viewed in the direction of incidence - the focal line starts near the surface 1a within the substrate and ends near the surface 1b within the substrate ($l = 0.75 \cdot d$).

[0053] It is particularly advantageous to realize the focal line positioning in such a way that at least one surface 1a, 1b is covered by the focal line, i.e. that the section of induced absorption 2c starts at least on one surface. In this way it is possible to achieve virtually ideal cuts avoiding ablation, feathering and particulation at the surface.

[0054] FIG. 4 depicts another applicable optical assembly 6. The basic construction follows the one described in FIG. 3A so that only the differences are described below. The depicted optical assembly is based upon the use of optics with a non-spherical free surface in order to generate the focal line 2b, which is shaped in such a way that a focal line of defined length l is formed. For this purpose, aspheres can be used as optic elements of the optical assembly 6. In FIG. 4, for example, a so-called conical prism, also often referred to as axicon, is used. An axicon is a special, conically cut lens which forms a spot source on a line along the optical axis (or transforms a laser beam into a ring). The layout of such an axicon is principally known to one of skill in the art; the cone angle in the example is 10°. The apex of the axicon labeled here with reference 9 is directed towards the incidence direction and centered on the beam center. As the focal line 2b of the axicon 9 already starts in its interior, substrate 1 (here aligned perpendicularly to the main beam axis) can be positioned in the beam path directly behind axicon 9. As FIG. 4 shows, it is also possible to shift substrate 1 along the beam direction due to the optical characteristics of the axicon without leaving the range of focal line 2b. The extensive section of the induced absorption 2c in the material of substrate 1 therefore extends over the entire substrate thickness d.

[0055] However, the depicted layout is subject to the following restrictions: As the focal line of axicon 9 already starts within the lens, a significant part of the laser energy is not focused into part 2c of focal line 2b, which is located within the material, in case of a finite distance between lens and material. Furthermore, length l of focal line 2b is related to the beam diameter for the available refraction indices and cone angles of axicon 9, which is why, in case of relatively thin materials (several millimeters), the total focal line is too long, having the effect that the laser energy is again not specifically focused into the material.

[0056] This is the reason for an enhanced optical assembly 6 which comprises both an axicon and a focusing lens. FIG. 5A depicts such an optical assembly 6 in which a first optical element (viewed along the beam direction) with a non-spherical free surface designed to form an extensive laser beam focal line 2b is positioned in the beam path of laser 3. In the case shown in FIG. 5A, this first optical element is an axicon 10 with a cone angle of 5°, which is positioned perpendicularly to the beam direction and centered on laser beam 3. The apex of the axicon is oriented towards the beam direction. A second, focusing optical element, here the plano-convex lens 11 (the curvature of which is oriented towards the axicon), is positioned in beam direction at a distance z1 from the axicon 10. The distance z1, in this case approximately 300 mm, is selected in such a way that the laser radiation formed by axicon 10 circularly incides on the marginal area of lens 11. Lens 11 focuses the circular radiation on the output side at a distance z2, in this case approximately 20 mm from lens 11, on a focal line 2b of a defined length, in this case 1.5 mm. The effective focal length of lens 11 is 25 mm here. The circular transformation of the laser beam by axicon 10 is labeled with the reference SR.

[0057] FIG. 5B depicts the formation of the focal line 2b or the induced absorption 2c in the material of substrate 1 according to FIG. 5A in detail. The optical characteristics of both elements 10, 11 as well as the positioning of them is selected in such a way that the extension l of the focal line 2b in beam direction is exactly identical with the thickness d of substrate 1. Consequently, an exact positioning of substrate 1 along the beam direction is required in order to position the focal line 2b exactly between the two surfaces 1a and 1b of substrate 1, as shown in FIG. 5B.

[0058] It is therefore advantageous if the focal line is formed at a certain distance from the laser optics, and if the greater part of the laser radiation is focused up to a desired end of the focal line. As described, this can be achieved by illuminating a primarily focusing element 11 (lens) only circularly on a required zone, which, on the one hand, serves to realize the required numerical aperture and thus the required spot size, on the other hand, however, the circle of diffusion diminishes in intensity after the required focal line 2b over a very short distance in the center of the spot, as a basically circular spot is formed. In this way, the crack formation is stopped within a short distance in the required substrate depth. A combination of axicon 10 and focusing lens 11 meets this requirement. The axicon acts in two different ways: due to the axicon 10, a usually round laser spot is sent to the focusing lens 11 in the form of a ring, and the asphericity of axicon 10 has the effect that a focal line is formed beyond the focal plane of the lens instead of a focal point in the focal plane. The length l of focal line 2b can be adjusted via the beam diameter on the axicon. The numerical aperture along the focal line, on the other hand, can be adjusted via the distance z1 axicon-lens and via the cone angle of the axicon. In this way, the entire laser energy can be concentrated in the focal line.

[0059] If the crack formation (i.e., defect line) is supposed to continue to the emergence side of the substrate, the circular illumination still has the advantage that, on the one hand, the laser power is used in the best possible way as a large part of the laser light remains concentrated in the required length of the focal line, on the other hand, it is possible to achieve a uniform spot size along the focal line - and thus a uniform separation process along the focal line - due to the circularly illuminated zone in conjunction with the desired aberration set by means of the other optical functions.

[0060] Instead of the plano-convex lens depicted in FIG. 5A, it is also possible to use a focusing meniscus lens or another higher corrected focusing lens (asphere, multi-lens system).

[0061] In order to generate very short focal lines 2b using the combination of an axicon and a lens depicted in FIG. 5A, it would be necessary to select a very small beam diameter of the laser beam inciding on the axicon. This has the practical disadvantage that the centering of the beam onto the apex of the axicon must be very precise and that therefore the result is very sensitive to direction variations of the laser (beam drift stability). Furthermore, a tightly collimated laser beam is very divergent, i.e. due to the light deflection the beam bundle becomes blurred over short distances.

[0062] As shown in FIG. 6, both effects can be avoided by inserting another lens, a collimating lens 12: this further, positive lens 12 serves to adjust the circular illumination of focusing lens 11 very tightly. The focal length f' of collimating lens 12 is selected in such a way that the desired circle diameter dr results from distance z1a from the axicon to the collimating lens 12, which is equal to f'. The desired width br of the ring can be adjusted via the distance z1b (collimating lens 12 to focusing lens 11). As a matter of pure geometry, the small width of the circular illumination leads to a short focal line. A minimum can be achieved at distance f'.

[0063] The optical assembly 6 depicted in FIG. 6 is thus based on the one depicted in FIG. 5A so that only the differences are described below. The collimating lens 12, here also designed as a plano-convex lens (with its curvature towards the beam direction) is additionally placed centrally in the beam path between axicon 10 (with its apex towards the beam direction), on the one side, and the plano-convex lens 11, on the other side. The distance of collimating lens 12 from axicon 10 is referred to as z1a, the distance of focusing lens 11 from collimating lens 12 as z1b, and the distance of the generated focal line 2b from the focusing lens 11 as z2 (always viewed in beam direction). As shown in FIG. 6, the circular radiation SR formed by axicon 10, which incides divergently and under the circle diameter dr on the collimating lens 12, is adjusted to the required circle width br along the distance z1b for an at least approximately constant circle diameter dr at the focusing lens 11. In the case shown, a very short focal line 2b is supposed to be generated so that the circle width br of approx. 4 mm at lens 12 is reduced to approx. 0.5 mm at lens 11 due to the focusing properties of lens 12 (circle diameter dr is 22 mm in the example).

[0064] In the depicted example it is possible to achieve a length of the focal line l of less than 0.5 mm using a typical laser beam diameter of 2 mm, a focusing lens 11 with a focal length f = 25 mm, and a collimating lens with a focal length f' = 150 mm. Furthermore applies Z1a = Z1b = 140 mm and Z2 = 15 mm.

[0065] **FIGS. 7A-7C** illustrate the laser-matter interaction at different laser intensity regimes. In the first case, shown in **FIG. 7A,** the unfocused laser beam 710 goes through a transparent substrate 720 without introducing any modification to it. In this particular case, the nonlinear effect is not present because the laser energy density (or laser energy per unit area illuminated by the beam) is below the threshold necessary to induce nonlinear effects. The higher the energy density, the higher is the intensity of the electromagnetic field. Therefore, as shown in **FIG. 7B** when the laser beam is focused by spherical lens 730 to a smaller spot size, as shown in **FIG. 7B**, the illuminated area is reduced and the energy density increases, triggering the nonlinear effect that will modify the material to permit formation of a fault line only in the volume where that condition is satisfied. In this way, if the beam waist of the focused laser is positioned at the surface of the substrate, modification of the surface will occur. In contrast, if the beam waist of the focused laser is positioned below the surface of the substrate, nothing happens at the surface when the energy density is below the threshold of the nonlinear optical effect. But at the focus 740, positioned in the bulk of the substrate 720, the laser intensity is high enough to trigger multi-photon non-linear effects, thus inducing damage to the material. Finally, as shown in **FIG. 7C** in the case of an axicon, as shown in **FIG. 7C**, the diffraction pattern of an axicon lens 750, or alternatively a Fresnel axicon, creates interference that generates a Bessel-shaped intensity distribution (cylinder of high intensity 760) and only in that volume is the intensity high enough to create nonlinear absorption and modification to the material 720. The diameter of cylinder 760, in which Bessel-shaped intensity distribution is high enough to create nonlinear absorption and modification to the material, is also the spot diameter of the laser beam focal line, as referred to herein. Spot diameter D of a Bessel beam can be expressed as $D = (2.4048\ \lambda)/(2\pi B)$, where λ is the laser beam wavelength and B is a function of the axicon angle.

[0066] Note that typical operation of such a picosecond laser described herein creates a "burst" 500 of pulses 500A. (See, for example, **FIGs. 8A and 8B**). Each "burst" (also referred to herein as a "pulse burst" 500) contains multiple individual pulses 500A (such as at least 2 pulses, at least 3 pulses, at least 4 pulses, at least 5 pulses, at least 10 pulses, at least 15 pulses, at least 20 pulses, or more) of very short duration. That is, a pulse bust is a “pocket” of pulses, and the bursts are separated from one another by a longer duration than the separation of individual adjacent pulses within each burst. Pulses 500A have pulse duration T_d of up to 100 psec (for example, 0.1 psec, 5 psec, 10 psec, 15 psec, 18 psec, 20 psec, 22 psec, 25 psec, 30 psec, 50 psec, 75 psec, or therebetween). The energy or intensity of each individual pulse 500A within the burst may not be equal to that of other pulses within the burst, and the intensity distribution of the multiple pulses within a burst 500 often follows an exponential decay in time governed by the laser design. Preferably, each pulse 500A within the burst 500 of the exemplary embodiments described herein is separated in time from the subsequent pulse in the burst by a duration T_p from 1 nsec to 50 nsec (e.g. 10-50 nsec, or 10-30 nsec, with the time often governed by the laser cavity design). For a given laser, the time separation T_p between adjacent pulses (pulse -to- pulse separation) within a burst 500 is relatively uniform (±10%). For example, in some embodiments, each pulse within a burst is separated in time from the subsequent pulse by approximately 20 nsec (50 MHz). For example, for a laser that produces pulse separation T_p of about 20 nsec, the pulse to pulse separation T_p within a burst is maintained within about ±10%, or about ±2 nsec. The time between each "burst" of pulses (i.e., time separation T_b between bursts) will be much longer (e.g., $0.25 \leq T_b \leq 1000$ microseconds, for example 1-10 microseconds, or 3-8 microseconds). In some of the exemplary embodiments of the laser described herein the time separation T_b is around 5 microseconds for a laser with pulse burst repetition rate or frequency of about 200 kHz. The laser burst repetition rate is relates to the time T_b between the first pulse in a burst to the first pulse in the subsequent burst (laser burst repetition rate = $1/T_b$). In some embodiments, the laser burst repetition frequency may be in a range of between about 1 kHz and about 4 MHz. More preferably, the laser burst repetition rates can be, for example, in a range of between about 10 kHz and 650 kHz. The time T_b between the first pulse in each burst to the first pulse in the subsequent burst may be 0.25 microsecond (4 MHz burst repetition rate) to 1000 microseconds (1 kHz burst repetition rate), for example 0.5 microseconds (2 MHz burst repetition rate) to 40 microseconds (25 kHz burst repetition rate), or 2 microseconds (500 kHz burst repetition rate) to 20 microseconds (50k Hz burst repetition rate). The exact timings, pulse durations, and burst repetition rates can vary depending on the laser design, but short pulses (T_d <20 psec and preferably $T_d \leq 15$ psec) of high intensity have been shown to work particularly well.

[0067] The energy required to modify the material can be described in terms of the burst energy - the energy contained within a burst (each burst 500 contains a series of pulses 500A), or in terms of the energy contained within a single laser pulse (many of which may comprise a burst). For these applications, the energy per burst can be from 25-750 μJ, more preferably 50-500 μJ, or 50-250 μJ. In some embodiments the energy per burst is 100-250 μJ. The energy of an individual pulse within the pulse burst will be less, and the exact individual laser pulse energy will depend on the number of pulses 500A within the pulse burst 500 and the rate of decay (e.g., exponential decay rate) of the laser pulses with time as shown in **FIGs.8A and 8B.** For example, for a constant energy/burst, if a pulse burst contains 10 individual laser pulses 500A, then each individual laser pulse 500A will contain less energy than if the same pulse burst 500 had only 2 individual laser pulses.

[0068] The use of a laser capable of generating such pulse bursts is advantageous for cutting or modifying transparent materials, for example glass. In contrast with the use of single pulses spaced apart in time by the repetition rate of the single- pulsed laser, the use of a pulse burst sequence that spreads the laser energy over a rapid sequence of pulses within the burst 500 allows access to larger timescales of high intensity interaction with the material than is possible with single-pulse lasers. While a single-pulse can be expanded in time, as this is done the intensity within the pulse must drop as roughly one over the pulse width. Hence if a 10 psec single pulse is expanded to a 10 nsec pulse, the intensity drop by roughly three orders of magnitude. Such a reduction can reduce the optical intensity to the point where non-linear absorption is no longer significant, and light material interaction is no longer strong enough to allow for cutting. In contrast, with a pulse burst laser, the intensity during each pulse 500A within the burst 500 can remain very high – for example three 10 psec pulses 500A spaced apart in time by approximately 10 nsec still allows the intensity within each pulse to be approximately three times higher than that of a single 10 psec pulse, while the laser is allowed to interact with the material over a timescale that is now three orders of magnitude larger. This adjustment of multiple pulses 500A within a burst thus allows manipulation of time-scale of the laser-material interaction in ways that can facilitate greater or lesser light interaction with a pre-existing plasma plume, greater or lesser light-material interaction with atoms and molecules that have been pre-excited by an initial or previous laser pulse, and greater or lesser heating effects within the material that can promote the controlled growth of microcracks. The required amount of burst energy to modify the material will depend on the substrate material composition and the length of the line focus used to interact with the substrate. The longer the interaction region, the more the energy is spread out, and higher burst energy will be required. The exact timings, pulse durations, and burst repetition rates can vary depending on the laser design, but short pulses (<15 psec, or ≤10 psec) of high intensity have been shown to work well with this technique. A defect line or a hole is formed in the material when a single burst of pulses strikes essentially the same location on the glass. That is, multiple laser pulses within a single burst correspond to a single defect line or a hole location in the glass. Of course, since the glass is translated (for example by a constantly moving stage) (or the beam is moved relative to the glass, the individual pulses within the burst cannot be at exactly the same spatial location on the glass. However, they are well within 1 μm of one another-i. e., they strike the glass at essentially the same location. For example, they may strike the glass at a spacing, sp, from one another where $0<sp\leq$ 500 nm. For example, when a glass location is hit with a burst of 20 pulses the individual pulses within the burst strike the glass within 250 nm of each other. Thus, in some embodiments 1 $nm<sp<250$ nm. In some embodiments 1 $nm<sp<100$ nm.

[0069] Multi-photon effects, or multi-photon absorption (MPA) is the simultaneous absorption of two or more photons of identical or different frequencies in order to excite a molecule from one state (usually the ground state) to a higher energy electronic state (ionization). The energy difference between the involved lower and upper states of the molecule can be equal to the sum of the energies of the two photons. MPA, also called induced absorption, can be can be a second-order, third-order process, or higher-order process, for example, that is several orders of magnitude weaker than linear absorption. MPA differs from linear absorption in that the strength of induced absorption can be proportional to the square or cube (or higher power law) of the light intensity, for example, instead of being proportional to the light intensity itself. Thus, MPA is a nonlinear optical process.

[0070] The lateral spacing (pitch) between the defect lines (damage tracks) is determined by the pulse rate of the laser as the substrate is translated underneath the focused laser beam. Only a single picosecond laser pulse burst is usually necessary to form an entire hole, but multiple bursts may be used if desired. To form damage tracks (defect lines) at different pitches, the laser can be triggered to fire at longer or shorter intervals. For cutting operations, the laser triggering generally is synchronized with the stage driven motion of the workpiece beneath the beam, so laser pulse bursts are triggered at a fixed spacing, such as for example every 1 micron, or every 5 microns. Distance, or periodicity, between adjacent perforations or defect lines along the direction of the fault line can be greater than 0.1 micron and less than or equal to about 20 microns in some embodiments, for example. For example, the spacing or periodicity between adjacent perforations or defect lines is between 0.5 and 15 microns, or between 3 and 10 microns, or between 0.5 micron and 3.0 microns. For example, in some embodiments the periodicity can be between 2 micron and 8 microns.

[0071] We discovered that using pulse burst lasers with certain volumetric pulse energy density ($\mu J/\mu m^3$) within the approximately cylindrical volume of the line focus re preferable to create the perforated contours in the glass. This can be achieved, for example, by utilizing pulse burst lasers, preferably with at least 2 pulses per burst and providing volumetric energy densities within the alkaline earth boro-aluminosilicate glasses (with low or no alkali) of about 0.005 $\mu J/\mu m^3$ or higher to ensure a damage track is formed, but less than 0.100 $\mu J/\mu m^3$ so as to not damage the glass too much, for example 0.005 $\mu J/\mu m^3$-0.100 $\mu J/\mu m^3$

Interior Contour Process

[0072] FIG. 1 illustrates the problem to be solved. A part 22 is to be cut out of a glass sheet 20. To release the outer contour of a part, additional release lines can be cut in the larger glass sheet that extend any crack lines to the edges of the sheet, allowing the glass to break into sections which can be removed. However, for interior contours such as those needed for a home button on a phone, creating additional release lines would cut through the part of interest. Thus the interior hole or slot is “locked in place”, and is difficult to remove. Even if the glass is high stress and crack propagate from perforation to perforation in the outer diameter of the hole or slot, the interior glass will not release, as the material will be too rigid and is held by compressional force.

[0073] One manner of releasing a larger hole is to first perforate the contour of the hole, and then follow up with a laser heating process, such as with a CO_2 laser, that heats up the inner glass piece until it softens and then is compliant enough to drop out. This works well for larger hole diameters and thinner materials. However, as the aspect ratio (thickness/diameter) of the glass plug gets very large, such methods have more difficulty. For example, with such methods, 10 mm diameter holes can be released from 0.7mm thick glass, but <4mm holes cannot always be released in the same glass thickness.

[0074] FIG. 8C illustrates a process that solves this problem, and has been successfully used to separate holes down to 1.5 mm diameter out of 0.7 mm thick code 2320 glass (ion-exchanged and non-ion exchanged), and also to create slots with widths and radii as small as 1.5 mm. Step 1 – A perforation of a first contour 24 is made in glass sheet 20 using the picosecond pulse burst process that defines the desired shape of the contour (e.g., hole, slot) to be cut. For example, for Corning’s code 2320 0.7 mm thick non-ion exchanged glass, 210 μJ bursts were used to pitch to perforate the material and to create damage tracks or defect lines at 4μm pitch. Depending on the exact material, other damage track spacings may also be employed, such as 1-15 microns, or 3-10 microns, or 3-7 microns. For ion-exchangeable glasses such as those described above, 3-7 micron pitch works well, but for other glasses such as the display glass Eagle XG, smaller pitches may be preferred, such a 1-3 microns. In the embodiments described herein, typical pulse burst laser powers are 10 W-150 Watts with laser powers of 25-60 Watts being sufficient (and optimum) for many glasses.

[0075] Step 2 – A second perforation line 26 is formed to form a second contour inside of the first contour, using the same laser process, but approximately a few hundred microns inside the first contour. This step is optional, but is often preferred, as the extra perforation is designed to act as a thermal barrier and to promote the fragmentation and removal of material inside the hole when the next process step is employed.

[0076] Step 3- A highly focused CO_2 laser 28 is used to ablate the material inside the hole, by tracing out the approximate path defined by the second perforation contour described above, or slightly (100μm) inside the 2nd contour. This will physically melt, ablate, and drive out the glass material inside of the hole or slot. For code 2320 0.7mm thick non-ion exchanged glass available from Corning Incorporated, a CO_2 laser power of about 14 Watts with a focused spot size of about100 μm diameter was used, and the CO_2 laser was translated around the path at a speed of about 0.35 m/min, executing 1-2 passes to completely remove the material, the number of passes begin dependent on the exact geometry of the hole or slot. In general, for this process step, the CO_2 beam would be defined as "focused" if it achieved a high enough intensity such that the glass material is melted and/or ablated by the high intensity. For example, the power density of the focused spot can be about 1750 W/mm^2, which would be accomplished with the above descrbed conditions, or could be from 500 W/mm^2 to 5000 W/mm^2, depending on the desired speed of traversal of the laser beam across the surface.

[0077] In addition, as shown in FIG. 9, a highly velocity assist gas such as pressurized air or nitrogen is blown through a nozzle surrounding the CO_2 laser head 32. This blows a directed stream of gas at the focused CO_2 laser spot on the glass, and helps force the loosened glass material out of the larger substrate. Multiple passes of the CO_2 laser, at the same inner radius or slightly different inner radii may be used, depending on the resistance of the material to the forced removal. In the case of the above high pressure compressed air was forced through a about 1 mm nozzle using a pressure of 80 psi. The nozzle was positioned about 1mm above the glass substrate during the ablation, and the CO_2 beam was focused such that it passed without vignetting through the aperture of the nozzle.

[0078] FIG. 9 shows a side view of the above this process, to illustrate how the CO_2 ablation and air nozzle will create loosened material and force it out of the interior of the hole or slot.

Sample Results:

[0079] FIG. 10 shows the results of the process, for a cover glass for a typical handheld phone. The geometry of the oblong hole (home button) was about 5.2mm by 16 mm, with about 1.5mm radius corners, and for the slot, it was 15 mm long, 1.6 mm wide, with about 0.75mm radii on the ends. Excellent edge quality (Ra of about 0.5 microns, no chipping observable under a 100X magnification microscope) and consistent material removal and separation were observed over >100 parts using this process.

[0080] FIG. 11 shows an angled view of the interior edge. The edge shows the same textured damage track or filament structure achieved with outer contours made with the same damage track or filamentation process, which is shown for comparison in FIG. 12. This indicates that the CO_2 ablation process described above has removed the loosened interior material without damaging the high quality, low roughness, and low sub-surface edge which is generally created with the picosecond perforation process described above.

[0081] FIG. 13 shows a top view of the cut edge of a slot made with the process described. No chirping or checking is observed on the edge of the contour. This contour has a radius of about 2mm.

[0082] As illustrated in **FIGs. 14A-14C**, the method to cut and separate transparent materials, and more specifically TFT glass compositions, is essentially based on creating a fault line 110 formed of a plurality of vertical defect lines 120 in the material or workpiece 130 to be processed with an ultra-short pulsed laser 140. The defect lines 120 extend, for example, through the thickness of the glass sheet, and are orthogonal to the major (flat) surfaces of the glass sheet. "Fault lines" are also referred to as "contours" herein. While fault lines or contours can be linear, like the fault line 110 illustrated in **FIG. 14A**, the fault lines or contours can also be nonlinear, having a curvature. Curved fault lines or contours can be produced by translating either the workpiece 130 or laser beam 140 with respect to the other in two dimensions instead of one dimension, for example. Depending on the material properties (absorption, CTE, stress, composition, etc.) and laser parameters chosen for processing the material 130, the creation of a fault line 110 alone can be enough to induce self-separation. In this case, no secondary separation processes, such as tension/bending forces or thermal stress created for example by a CO_2 laser, are necessary. As illustrated in **FIG. 14A**, a plurality of defect lines can define a contour. The separated edge or surface with the defect lines is defined by the contour. The induced absorption creating the defect lines can produce particles on the separated edge or surface with an average diameter of less than 3 microns, resulting in a very clean cutting process.

[0083] In some cases, the created fault line is not enough to separate the material spontaneously, and a secondary step may be necessary. While the perforated glass part may be placed in an chamber such as an oven to create a bulk heating or cooling of the glass part, to create thermal stress to separate the parts along the defect line, such a process can be slow and may require large ovens or chambers to accommodate many arts or large pieces or perforated glass. If so desired, a second laser can be used to create thermal stress to separate it, for example. In the case of TFT glass compositions, separation can be achieved, after the creation of a fault line, by application of mechanical force or by using a thermal source (e.g., an infrared laser, for example a CO_2 laser) to create thermal stress and force separation of the material. Another option is to have the CO_2 laser only start the separation and then finish the separation manually. The optional CO_2 laser separation is achieved, for example, with a defocused continuous wave (cw) laser emitting at 10.6 microns and with power adjusted by controlling its duty cycle. Focus change (i.e., extent of defocusing up to and including focused spot size) is used to vary the induced thermal stress by varying the spot size. Defocused laser beams include those laser beams that produce a spot size larger than a minimum, diffraction-limited spot size on the order of the size of the laser wavelength. For example, CO2 laser spot sizes of 1 to 20 mm, for example 1 to 12 mm, 3 to 8 mm, or about 7 mm, 2 mm, and 20 mm can be used for CO_2 lasers, for example, with a CO_2 10.6 μm wavelength laser. Other lasers, whose emission wavelength is also absorbed by the glass, may also be used, such as lasers with wavelengths emitting in the 9-11 micron range, for example. In such cases CO_2 laser with power levels between 100 and 400 Watts may be used, and the beam may be scanned at speeds of 50-500 mm/sec along or adjacent to the defect lines, which creates sufficient thermal stress to induce separation. The exact power levels, spot sizes, and scanning speeds chosen within the specified ranges may depend on the material use, its thickness, coefficient of thermal expansion (CTE), elastic modulus, since all of these factors influence the amount of thermal stress imparted by a specific rate of energy deposition at a given spatial location. If the spot size is too small (i.e. <1 mm), or the CO_2 laser power is too high (>400W), or the scanning speed is too slow (less than 10 mm/sec), the glass may be over heated, creating ablation, melting or thermally generated cracks in the glass, which are undesirable, as they will reduce the edge strength of the separated parts. Preferably the CO_2 laser beam scanning speed is >50 mm/sec, in order to induce efficient and reliable part separation. However, if the spot size created by the CO_2 laser is too large (>20 mm), or the laser power is too low (< 10W, or in some cases <30W), or the scanning speed is too high (>500 mm/sec), insufficient heating occurs which results in too low a thermal stress to induce reliable part separation.

[0084] For example, in some embodiments, a CO_2 laser power of 200 Watts may be used, with a spot diameter at the glass surface of approximately 6 mm, and a scanning speed of 250 mm/sec to induce part separation for 0.7 mm thick Corning Eagle XG® glass that has been perforated with the above mentioned psec laser. For example a thicker Corning Eagle XG® glass substrate may require more CO_2 laser thermal energy per unit time to separate than a thinner Eagle XG® substrate, or a glass with a lower CTE may require more CO_2 laser thermal energy to separate than a glass with a lower CTE. Separation along the perforated line will occur very quickly (less than 1 second) after CO_2 spot passes a given location, for example within 100 milliseconds, within 50 milliseconds, or within 25 milliseconds.

[0085] Distance, or periodicity, between adjacent defect lines 120 along the direction of the fault lines 110 can be greater than 0.1 micron and less than or equal to about 20 microns in some embodiments, for example. For example, in some embodiments, the periodicity between adjacent defect lines 120 may be between 0.5 and 15 microns, or between 3 and 10 microns, or between 0.5 micron and 3.0 microns. For example, in some embodiments the periodicity between adjacent defect lines 120 can be between 0.5 micron and 1.0 micron.

[0086] There are several methods to create the defect line. The optical method of forming the line focus can take multiple forms, using donut shaped laser beams and spherical lenses, axicon lenses, diffractive elements, or other methods to form the linear region of high intensity. The type of laser (picosecond, femtosecond, etc.) and wavelength (IR, green, UV, etc.) can also be varied, as long as sufficient optical intensities are reached to create breakdown of the substrate material in the region of focus to create breakdown of the substrate material or glass workpiece, through nonlinear optical effects. Preferably, the laser is a pulse burst laser which allows for control of the energy deposition with time by adjusting the number of pulses within a given burst.

[0087] In the present application, an ultra-short pulsed laser is used to create a high aspect ratio vertical defect line in a consistent, controllable and repeatable manner. The details of the optical setup that enables the creation of this vertical defect line are described below, and in U.S. Application No. 61/752,489 filed on January 15, 2013, the entire contents of which are incorporated by reference as if fully set forth herein. The essence of this concept is to use optics to create a line focus of a high intensity laser beam within a transparent part. One version of this concept is to use an axicon lens element in an optical lens assembly to create a region of high aspect ratio, taper-free microchannels using ultra-short (picoseconds or femtosecond duration) Bessel beams. In other words, the axicon condenses the laser beam into a high intensity region of cylindrical shape and high aspect ratio (long length and small diameter). Due to the high intensity created with the condensed laser beam, nonlinear interaction of the electromagnetic field of the laser and the substrate material occurs and the laser energy is transferred to the substrate to effect formation of defects that become constituents of the fault line. However, it is important to realize that in the areas of the material where the laser energy intensity is not high (e.g., glass volume of substrate surrounding the central convergence line), the material is transparent to the laser and there is no mechanism for transferring energy from the laser to the material. As a result, nothing happens to the glass or workpiece when the laser intensity is below the nonlinear threshold.

[0088] The methods described above provide the following benefits that may translate to enhanced laser processing capabilities and cost savings and thus lower cost manufacturing. The cutting process offers:

[0089] 1) Full separation of interior contours being cut: the methods described above are capable of completely separating/cutting holes and slots in a clean and controlled fashion in ion-exchangeable glass (such as Gorilla® glass, Corning glass codes 2318, 2319, 2320 or the like) as produced by the fusion draw process, or other glass forming processes, before the glass part has undergone chemical strengthening.

[0090] 2) Separation of holes/slots with very small dimensions: Other processes may be used to heat and induce softening of a glass plug which can allow it to drop out of a glass sheet. However, as the aspect ratio (thickness/diameter) of the glass plug gets very large, such methods fail. For example, heating (not ablation) of the interior glass plug will drop out 10 mm diameter holes out of 0.7 mm thick glass, but if the diameter of the hole is reduced to 4 mm, such processes will not work. However, the process disclosed here has been used to remove glass plugs that have dimensions as small as 1.5mm (diameter of a circle, or width of a slot) in 0.7 mm thick glass.

[0091] 3) Reduced subsurface defects and excellent edge quality: Due to the ultra-short pulse interaction between laser and material, there is little thermal interaction and thus a minimal heat affected zone that can result in undesirable stress and micro-cracking. In addition, the optics that condense the laser beam into the glass creates defect lines that are typically 2 to 5 microns diameter on the surface of the part. After separation, the subsurface damage is <75 µm, and can be adjusted to be <25µm. The roughness of the separated surface (or cut edge), results particularly from the spot size or the spot diameter of the focal line. A roughness of the separated (cut) surface which can be, for example, 0.1 to 1 microns or for example 0.25 to 1 microns), can be characterized, for example, by an Ra surface roughness statistic (roughness arithmetic average of absolute values of the heights of the sampled surface, which include the heights of bumps resulting from the spot diameter of the focal line). The surface roughness generated by this process is often <0.5µm (Ra), and can be as low as 0.1µm (Ra). This has great impact on the edge strength of the part as strength is governed by the number of defects, their statistical distribution in terms of size and depth. The higher these numbers are the weaker the edges of the part will be. In addition, if any mechanical finishing processes such as grinding and polishing are later used to modify the edge shape, the amount of material removal required will be lower for parts with less sub-surface damage. This reduces or eliminates finishing steps, lower part cost. The hole and slot release process described here takes full advantage of the high-quality edge created by this line-focus picosecond laser perforation process – it ensures that the removal of the interior glass material is done in a manner that cleanly releases the glass along this perforation line, and does not induce ablative damage, micro-cracking, or other defects to the desired part edge.

[0092] Speed: Unlike processes which use focused laser to purely ablate the material around the inner contour, this laser process is a single pass process for the perforation line. The perforated hole contour may be created by the picosecond laser process described herein at speeds of 80-1000mm/sec, depending only on the acceleration capabilities of the stages involved. This is in contrast to ablative hole and slot drilling methods, where material is removed "layer by layer" and requires many passes or long residence times per location of the laser beam.

[0093] Process cleanliness: the methods described above are capable of separating/cutting glass or other transparent brittle materials in a clean and controlled fashion. It is very challenging to use conventional ablative or thermal laser processes because they tend to trigger heat affected zones that induce micro-cracks and fragmentation of the glass into several smaller pieces. The characteristics of the laser pulses and the induced interactions with the material of the disclosed method avoid all of these issues because they occur in a very short time scale and the material transparency to the laser radiation minimizes the induced thermal effects. Since the defect line is created within the object, the presence of debris and adhered particles during the cutting step is virtually eliminated. If there are any particulates resulting from the created defect line, they are well contained until the part is separated.

Cutting complex profiles and shapes in different sizes

[0094] The methods described above enable cutting/separation of glass and other substrates following many forms and shapes, which is a limitation in other competing technologies. Tight radii may be cut (<2mm), allowing creation of small holes and slots (such as required for speakers/microphone in a cell phone application). Also, since the defect lines strongly control the location of any crack propagation, those method give great control to the spatial location of a cut, and allow for cut and separation of structures and features as small as a few hundred microns.

Elimination of Process Steps

[0095] The process to fabricate glass plates from the incoming glass panel to the final size and shape involves several steps that encompass cutting the panel, cutting to size, finishing and edge shaping, thinning the parts down to their target thickness, polishing, and even chemically strengthening in some cases. Elimination of any of these steps will improve manufacturing cost in terms of process time and capital expense. The methods described above may reduce the number of steps by, for example:

[0096] Reduced debris and edge defects generation - potential elimination of washing and drying stations

[0097] Cutting the sample directly to its final size, shape and thickness - eliminating need for finishing lines.

[0098] Thus, according to some embodiments, a glass article has at least one inner contour edge with plurality of defect lines extending perpendicular to the face of the glass sheet at least 250 μm, the defect lines each having a diameter less than or equal to about 5 μm. For example, a glass article has at least one inner contour edge having a plurality of defect lines extending perpendicular to the major (i.e., large relative to the sides) flat face of the glass sheet at least 250 μm, the defect lines each having a diameter less than or equal to about 5μm. In some embodiments, the smallest dimension or width of the interior contour defined by the inner contour edge is less than 5 mm, for example it may be 0.1 mm to 3 mm in width (or diameter), e.g, 0.5 mm to 2 mm. According to some embodiments, the glass article comprises post-ion exchange glass. According to some embodiments, the defect lines extend the full thickness of the at least one inner contour edge. According to at least some embodiments, the at least one inner contour edge has an Ra surface roughness less than about 0.5 μm. According to at least some embodiments, the at least one inner contour edge has subsurface damage up to a depth less than or equal to about 75 μm. In at least some embodiments, of the glass article the defect lines extend the full thickness of the edge. The distance between the defect lines is, for example, less than or equal to about 7 μm.

[0099] The relevant teachings of all patents, published applications and references cited herein are incorporated by reference in their entirety.

[00100] While exemplary embodiments have been disclosed herein, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

CLAIMS

What is claimed is:

1. A method of laser drilling a material comprising:

focusing a pulsed laser beam into a laser beam focal line, viewed along the beam propagation direction;

directing the laser beam focal line into the material at a first location, the laser beam focal line generating an induced absorption within the material, the induced absorption producing a damage track along the laser beam focal line within the material;

translating the material and the pulsed laser beam relative to each other starting from the first location along a first closed contour, thereby laser drilling a plurality of holes along the first closed contour within the material; and

directing a focused carbon dioxide (CO2) laser into the material around a second closed contour contained within the first closed contour to facilitate removal of an inner plug of the material along the first closed contour.

2. A glass article prepared by the method of claim 1.

3. A glass article having at least one inner contour edge having a plurality of defect lines extending perpendicular to the major face of the glass sheet at least 250 µm, the defect lines each having a diameter less than or equal to about 5 µm.

4. The method of claim 1 or the article of claim 2, further comprising:

directing the laser beam focal line into the material at a second location, the laser beam focal line generating an induced absorption within the material, the induced absorption producing a damage track along the laser beam focal line within the material; and

translating the material and the pulsed laser beam relative to each other starting from the second location along a third closed contour, thereby laser drilling a plurality of damage tracks along the third closed contour within the material, the third closed contour contained within the first closed contour.

5. The method or article of claim 4, wherein the second closed contour and the third closed contour coincide.

6. The method or article of claim 4, wherein the second closed contour is contained between the first closed contour and third closed contour.

7. The method or article of any of claims 1-2 or 4-6, further comprising directing an assist gas toward the material and collinear with the CO_2 laser beam.

8. The method or article of any of claims 1-2 or 4-7, wherein removal of the inner plug defines an opening in the material, the opening having a width between 0.5 mm and 100 mm.

9. The method or article of any of claims 1-2 or 4-8, wherein removal of the inner plug defines a slot in the material that has a width between 0.5 mm and 100 mm.

10. The method or article of any of claims 1-2 or 4-9, wherein the induced absorption produces subsurface damage at the first contour of up to a depth less than or equal to about 75 μm within the material.

11. The method or article of any of claims 1-2 or 4-10, wherein the induced absorption produces an Ra surface roughness at the first contour of less than or equal to about 0.5 μm.

12. The method or article of any preceding claim, wherein the material has a thickness in a range of between about 100 μm and about 8 mm.

13. The method or article of any of claims 1-2 or 4-12, wherein the material and pulsed laser beam are translated relative to each other at a speed in a range of between about 1 mm/sec and about 3400 mm/sec.

14. The method or article of any of claims 1-2 or 4-13, wherein a pulse duration of the pulsed laser beam is in a range of between greater than about 1 picosecond and less than about 100 picoseconds.

15. The method or article of any of claims 1-2 or 4-14, wherein a repetition rate of the pulsed laser beam is in a range of between about 1 kHz and 2 MHz.

16. The method or article of any of claims 1-2 or 4-15, wherein the pulsed laser beam has an energy per burst measured at the material greater than 40 μJ per mm thickness of material.

17. The method or article of any of claims 1-2 and 4-16, wherein the pulses are produced in pulse bursts of at least two pulses separated by a duration in a range of between about 1 nsec and about 50 nsec, and the burst repetition frequency is in a range of between about 1 kHz and about 650 kHz.

18. The method or article of any preceding claim, wherein the laser beam focal line has a length in a range of between about 0.1 mm and about 100 mm.

19. The glass article or method of any preceding claim, wherein the smallest dimension or width of the inner contour defined by the inner contour edge is less than 5 mm.

20. The glass article of claim 19, wherein a distance between the defect lines is less than or equal to about 7 μm.

21. The method or article of any of claims 1-2 or 4-20, wherein the pulsed laser produces pulse bursts with at least 2 pulses per pulse burst.

22. The method or article of any of claims 1-2 or 4-21, wherein the pulsed laser has laser power of 10W-150W and produces pulse bursts with at least 2 pulses per pulse burst.

23. The method or article of any of claims 1-2 or 4-22, wherein the pulsed laser has laser power of 10W-100 W and produces pulse bursts with at least 2 - 25 pulses per pulse burst.

24. The method or article of any of claims 1-2 or 4-23, wherein the pulsed laser has laser power of 10W-100W and the workpiece or the laser beam is translated relative to one another at a rate of at least 0.25 m/sec.

25. The glass article of claims 2, or 3 wherein:

(i) said major face of glass sheet is flat; and/or

(ii) the smallest dimension or width of the inner contour defined by the inner contour edge is less than 5 mm; and/or

(iii) the glass article comprises post-ion exchange glass; and/or

(iv) the defect lines extend the full thickness of the at least one inner contour edge; and/or

(v) the at least one inner contour edge has an Ra surface roughness less than about 0.5 μm.

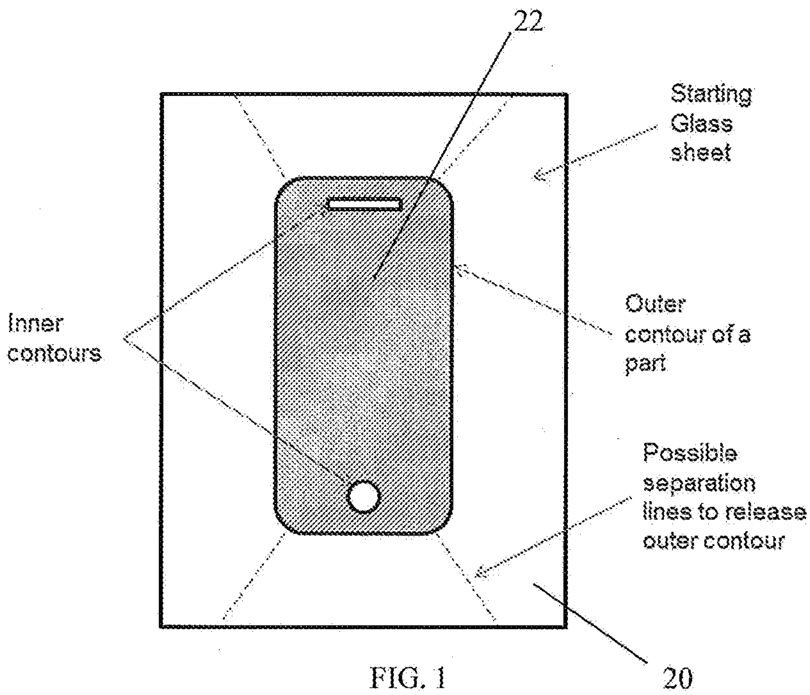

22
Starting
Glass
sheet
Inner
contours
Outer
contour of a
part
Possible
separation
lines to release
outer contour
20

FIG. 1

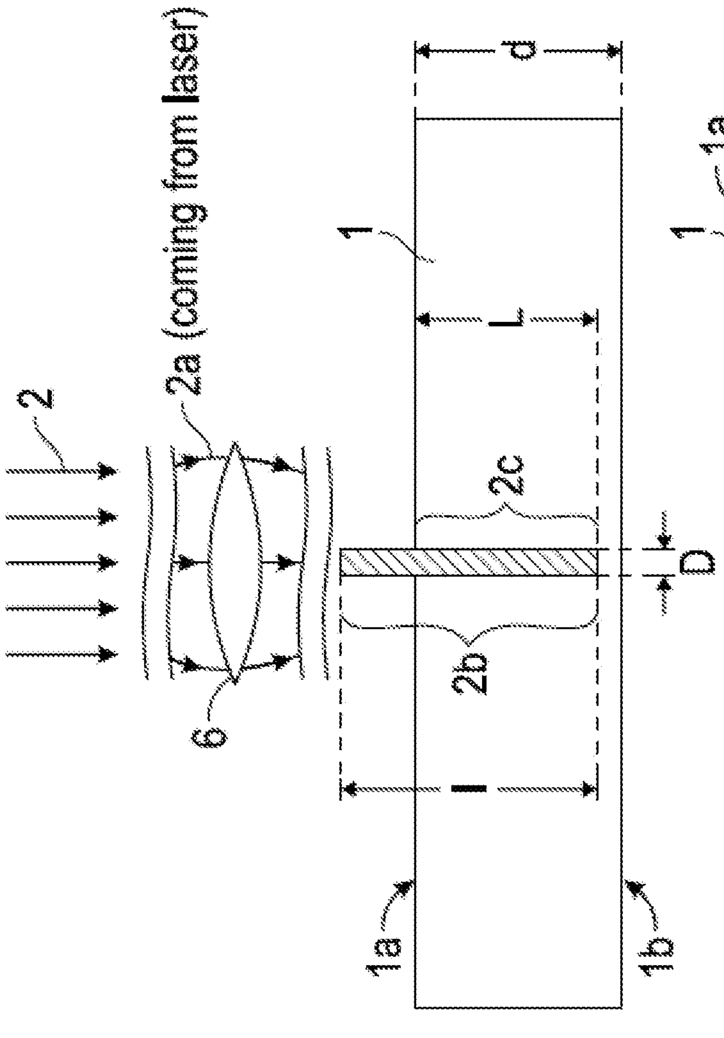


FIG. 2A

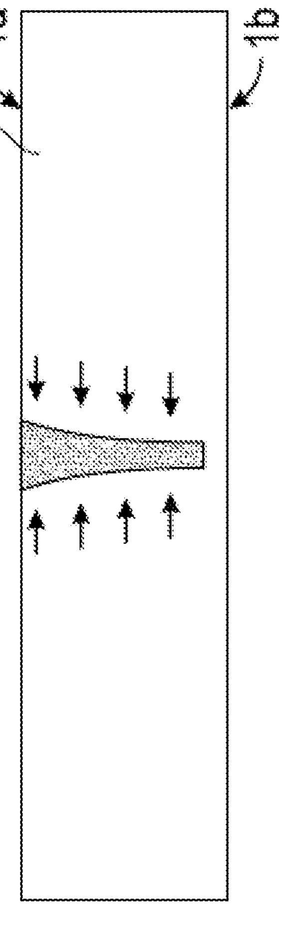


FIG. 2B

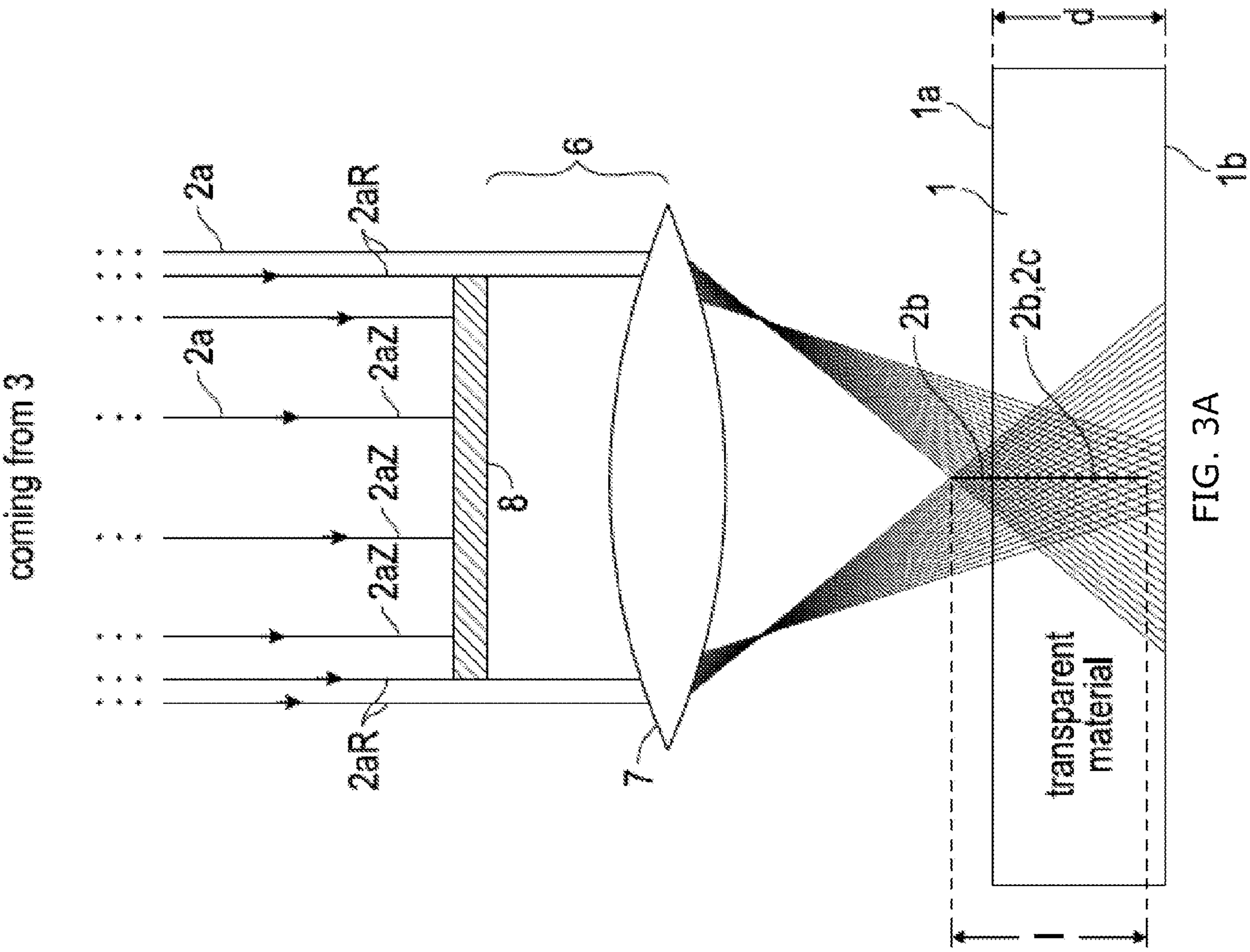

coming from 3
2a
2aR
2a
2aZ
2aZ
2aZ
2aR
6
8
7
2b
2b,2c
1
1a
1b
d
l
transparent material

FIG. 3A

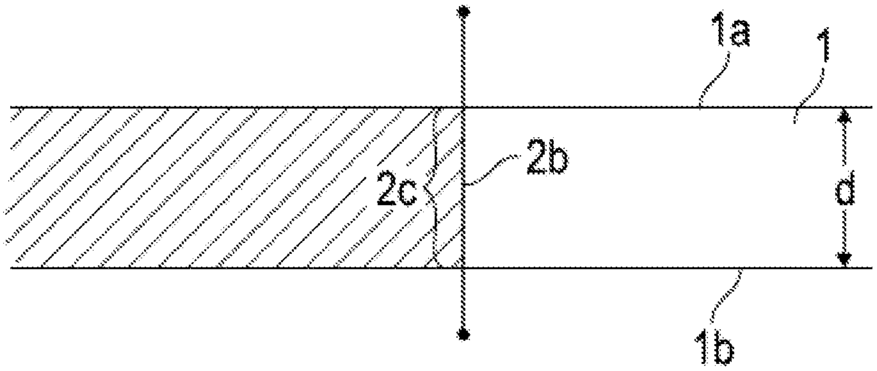


FIG. 3B-1

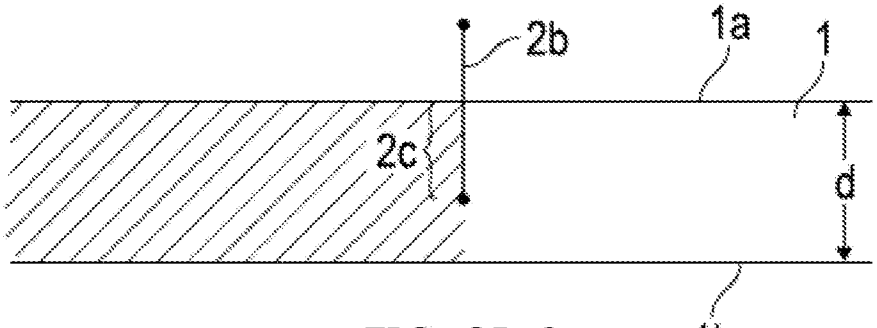


FIG. 3B-2

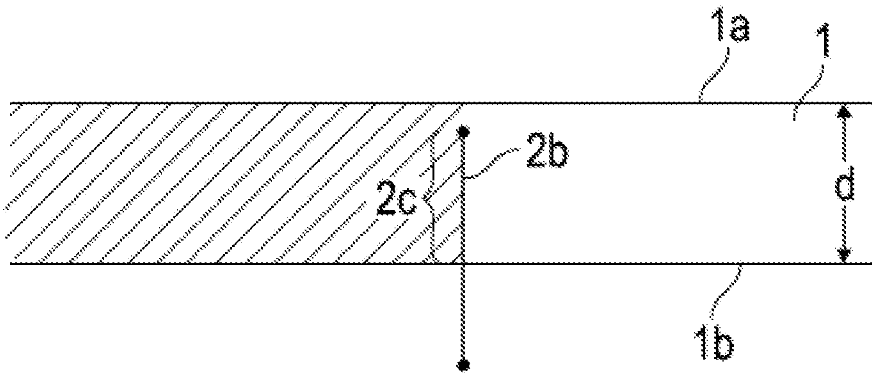


FIG. 3B-3

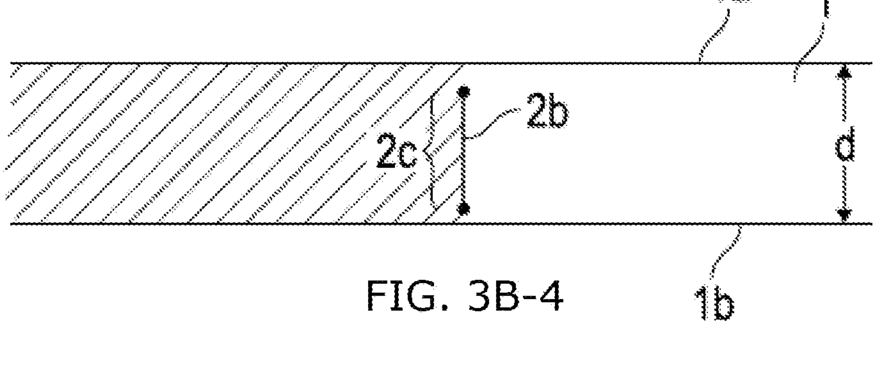


FIG. 3B-4

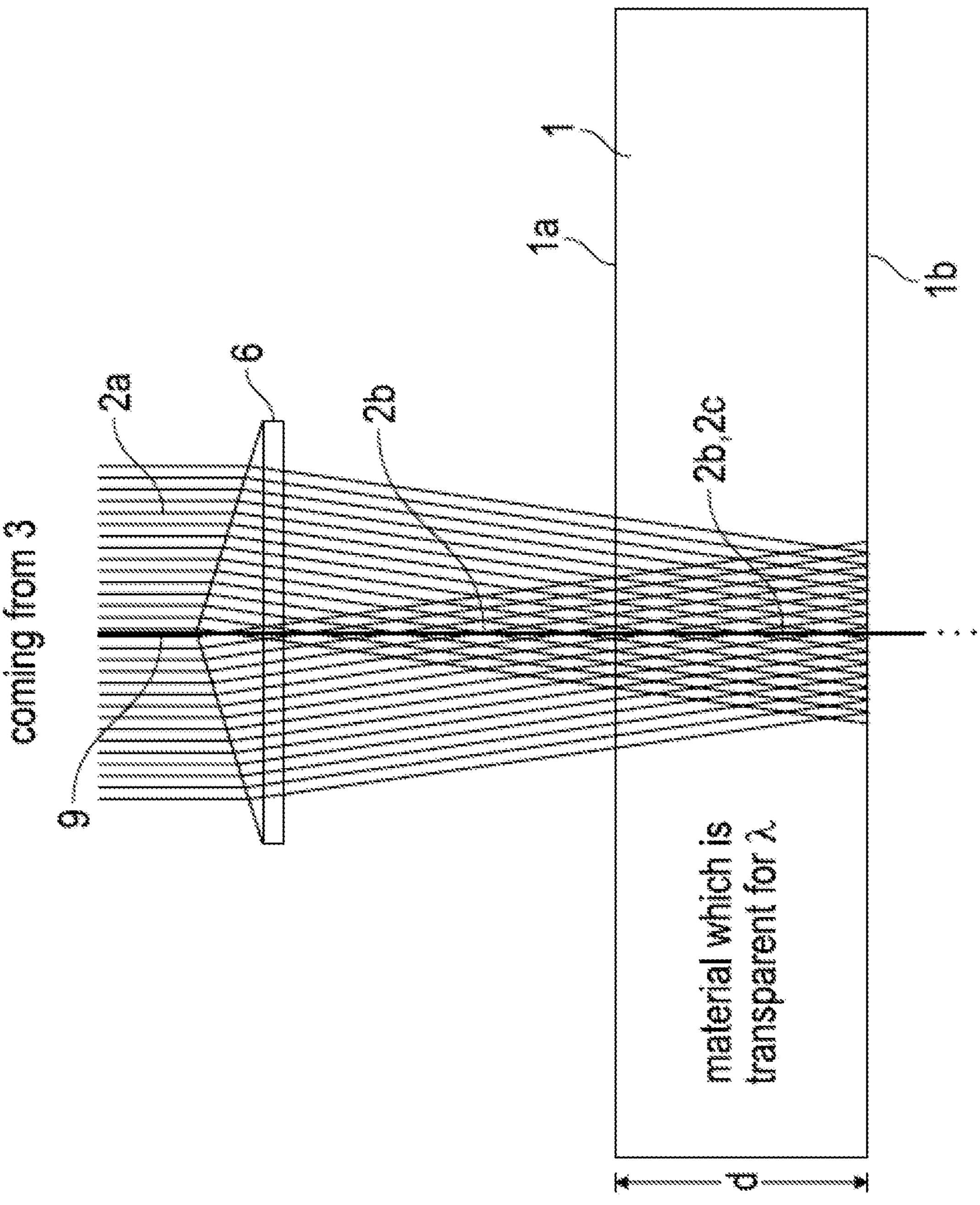

coming from 3
9
2a
6
2b
2b,2c
1
1a
1b
material which is
transparent for λ
d

FIG. 4

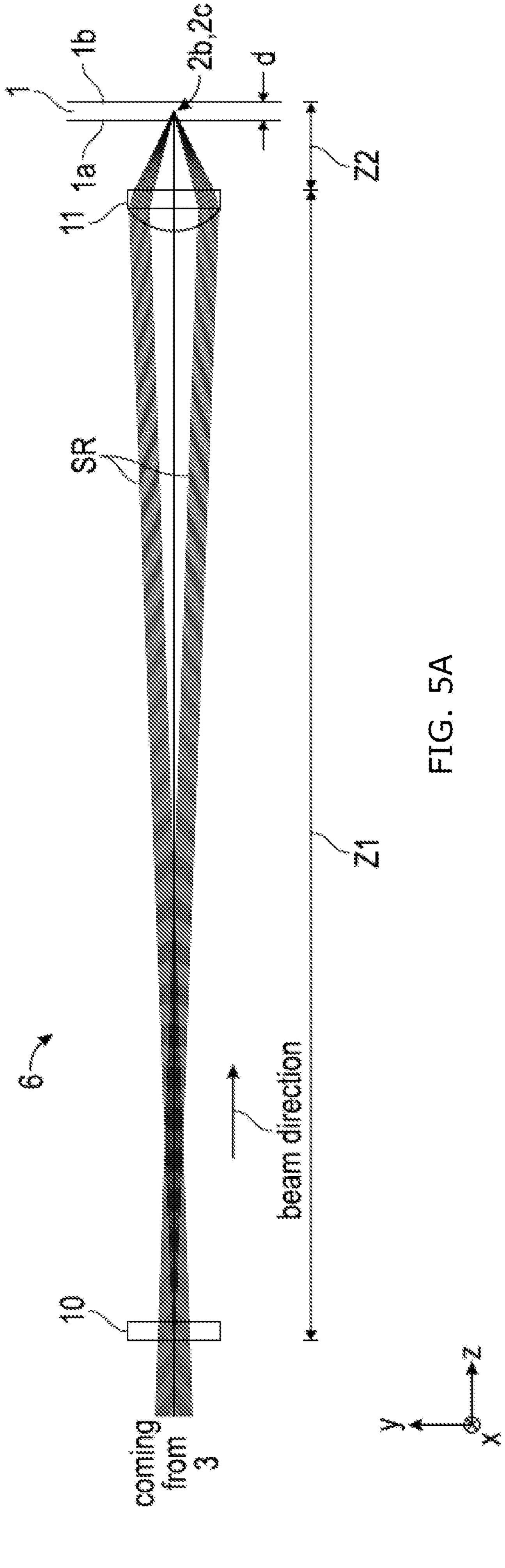


FIG. 5A

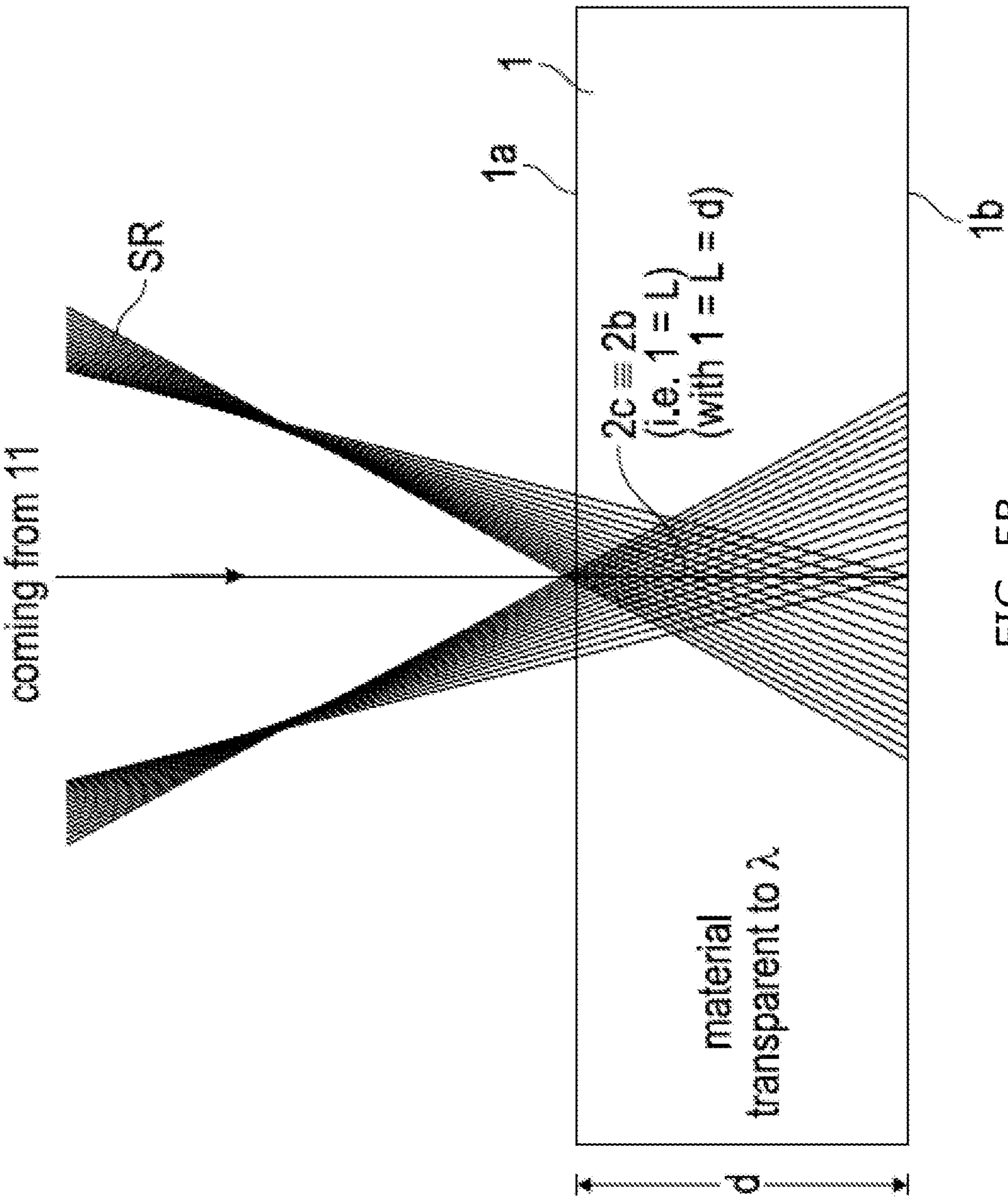

coming from 11
SR
1a
1
1b
2c = 2b
(i.e. 1 = L)
(with 1 = L = d)
material
transparent to λ
d

FIG. 5B

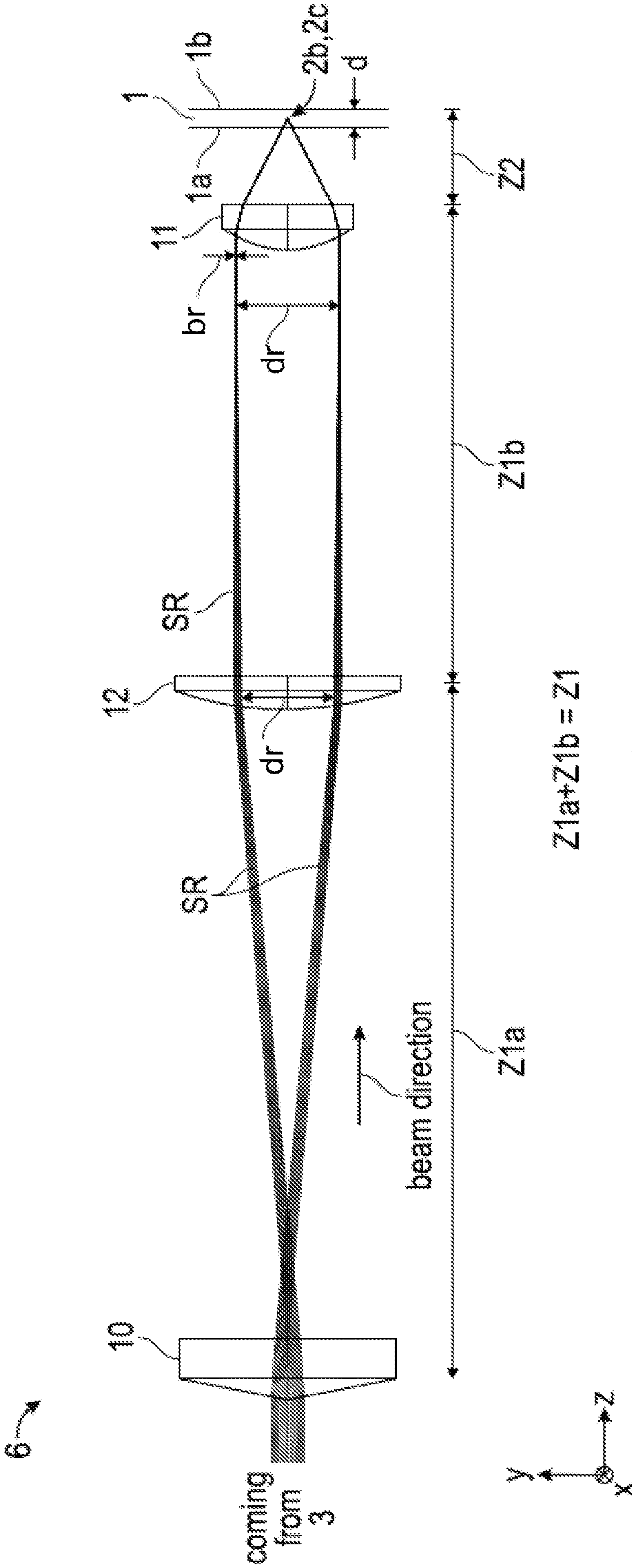

1b
1
2b,2c
d
1a
Z2
11
br
dr
Z1b
SR
12
dr
SR
beam direction
Z1a
10
6
coming from 3
y
z
x
Z1a+Z1b = Z1

FIG. 6

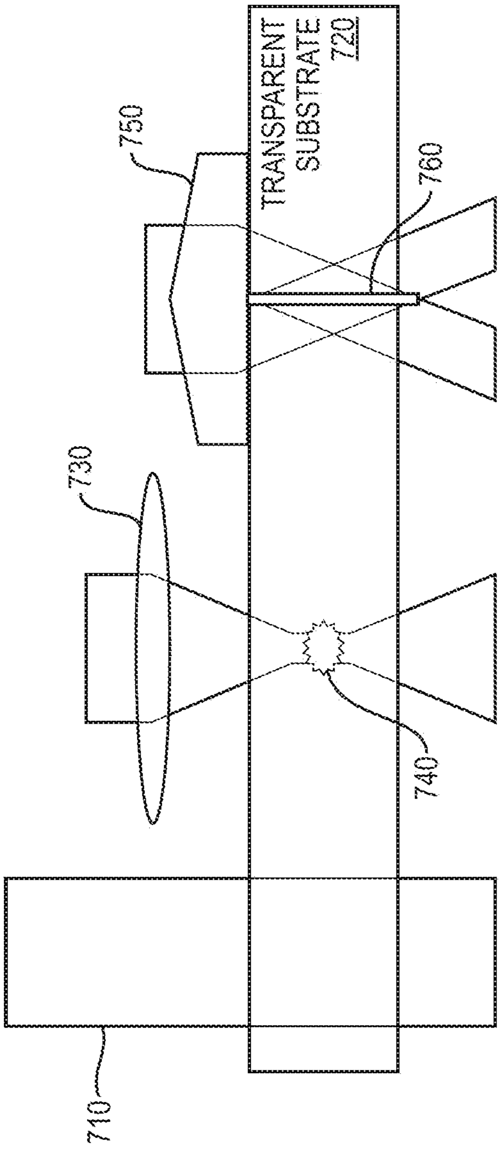
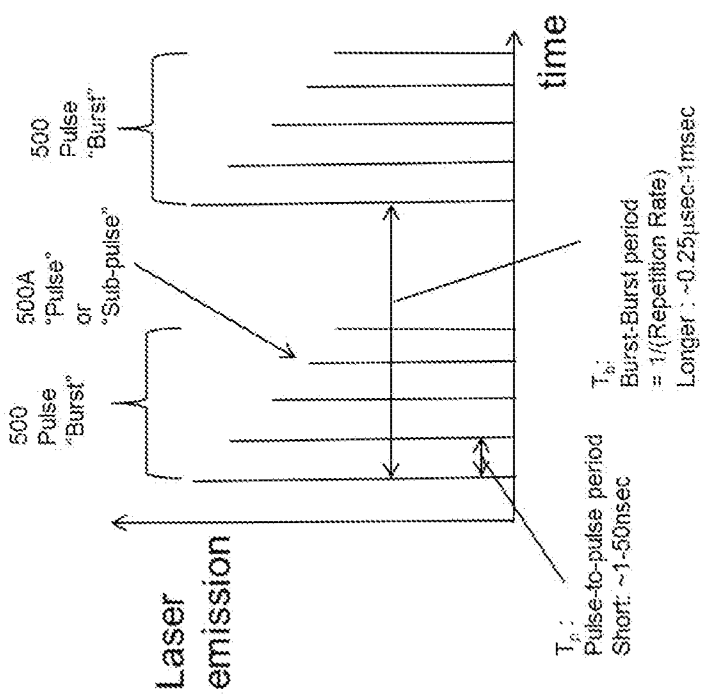


FIG. 7A

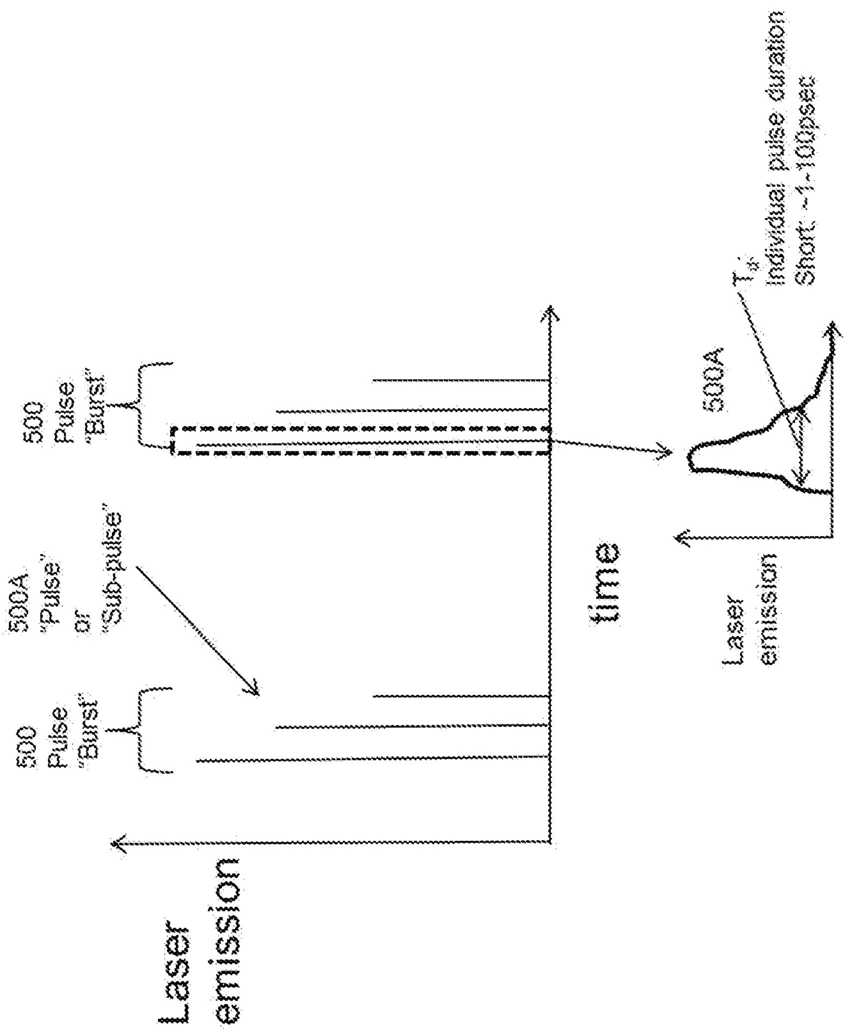
FIG. 7B

FIG. 7C



500 Pulse "Burst"
500A "Pulse" or "Sub-pulse"
500 Pulse "Burst"
time
Laser emission
T_p: Pulse-to-pulse period Short: ~1-50nsec
T_b: Burst-Burst period = 1/(Repetition Rate) Longer: ~0.25µsec-1msec

FIG. 8B



500 Pulse "Burst"
500A "Pulse" or "Sub-pulse"
500 Pulse "Burst"
time
Laser emission
500A
Laser emission
T_d: Individual pulse duration Short: ~1-100psec

FIG. 8A

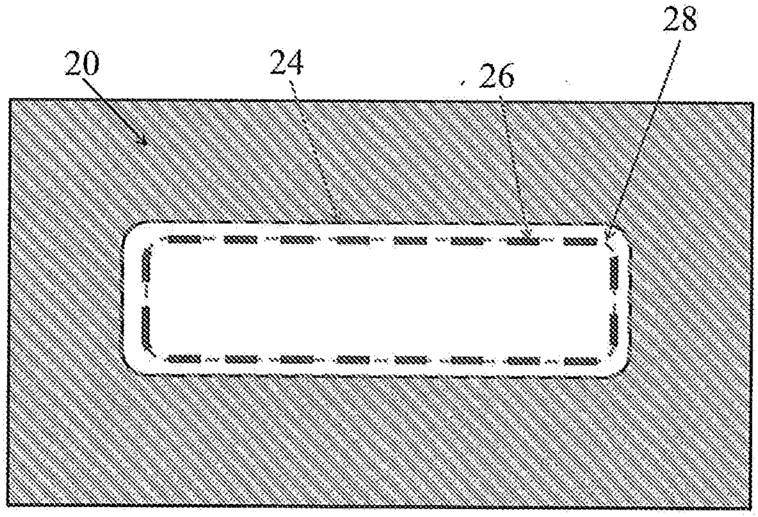


FIG. 8C

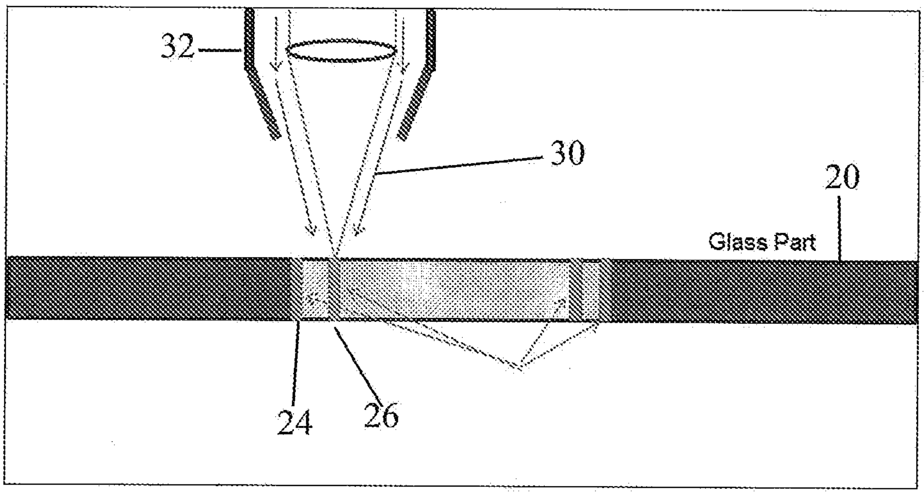


FIG. 9

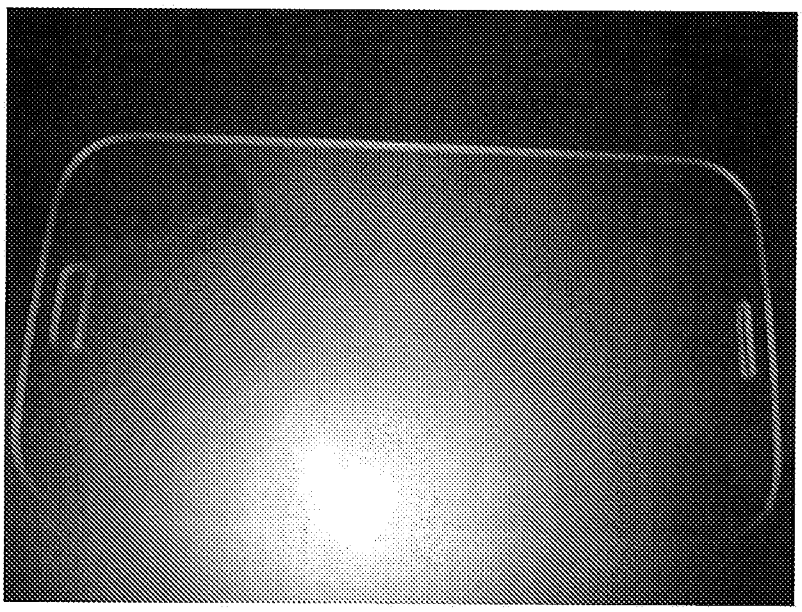


FIG. 10

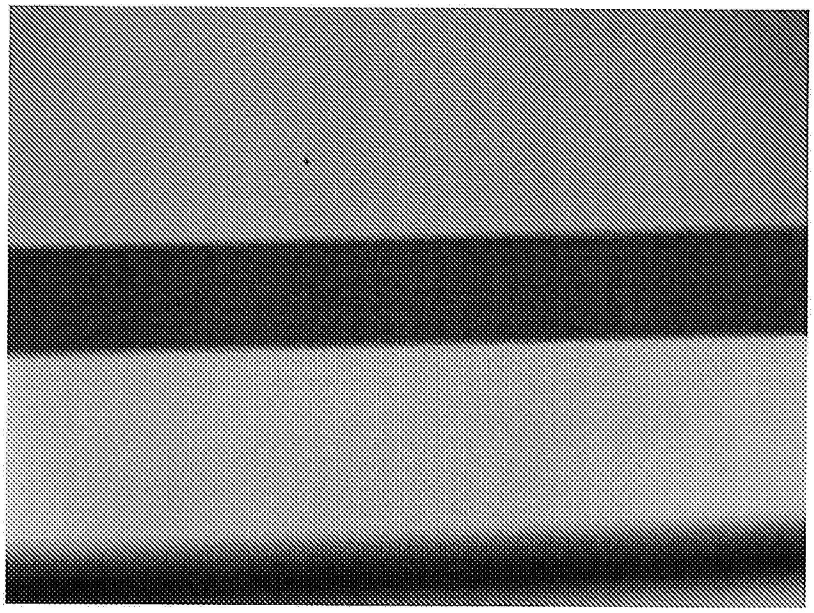


FIG. 11

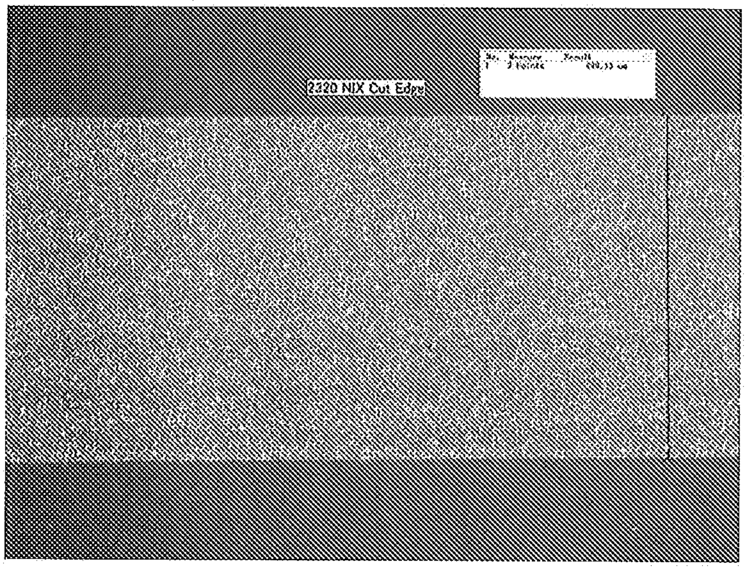


FIG. 12

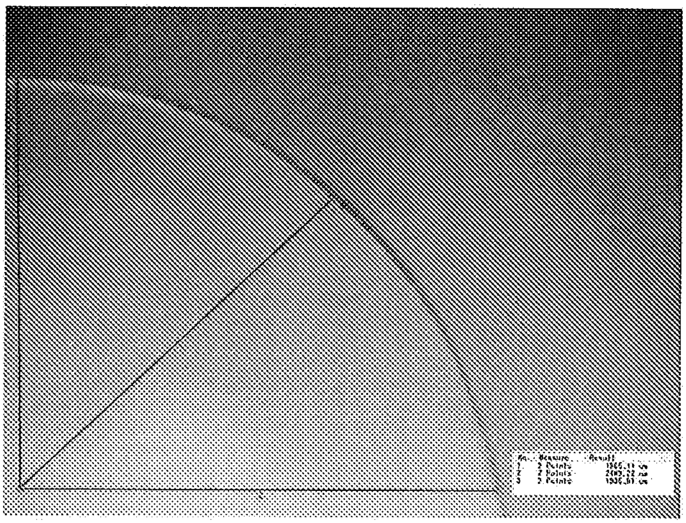


FIG. 13

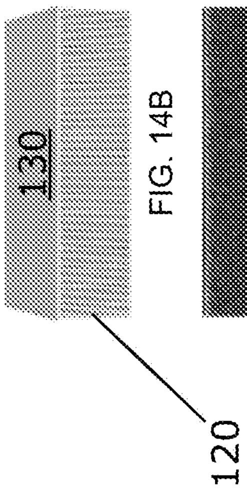


FIG. 14B

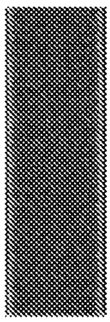


FIG. 14C

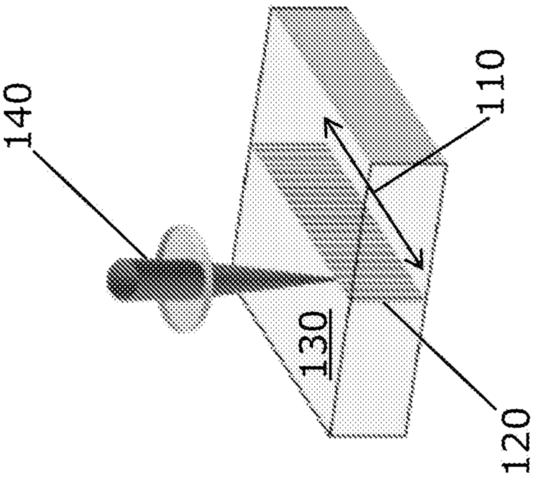


FIG. 14A