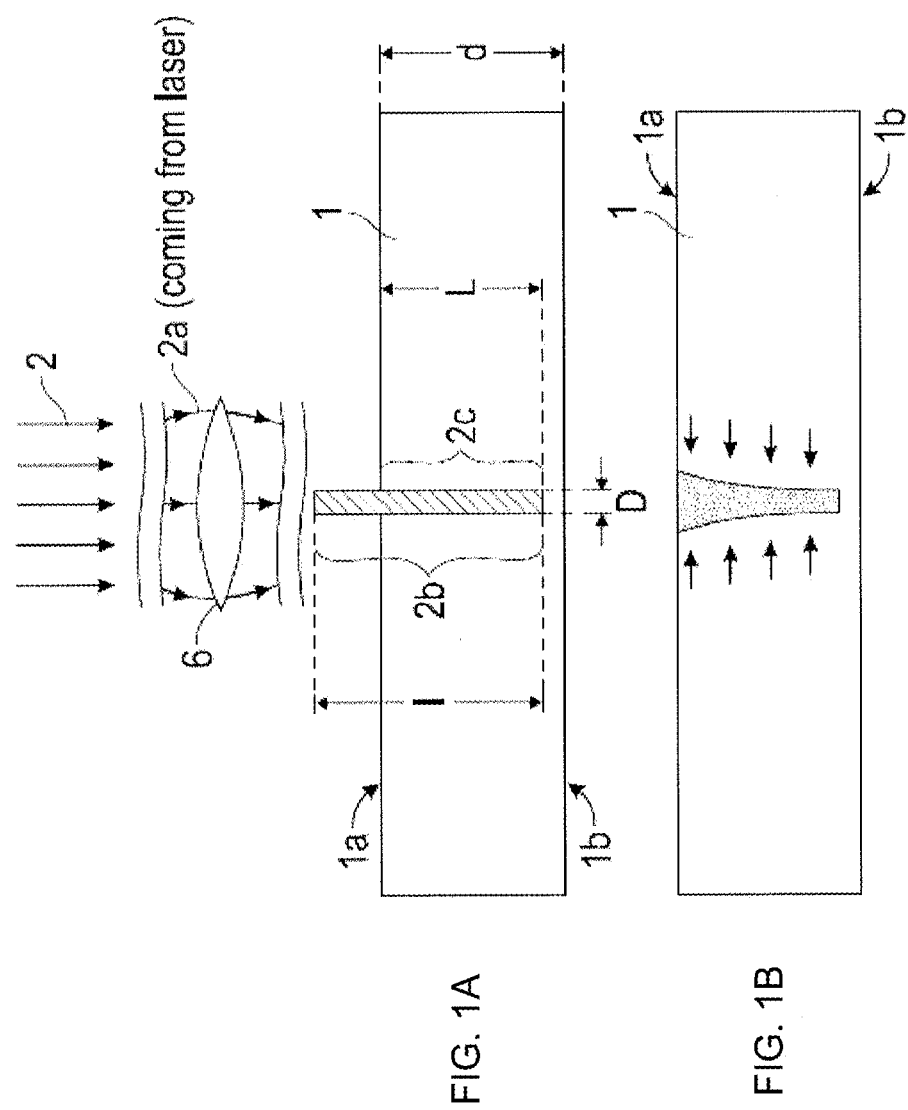
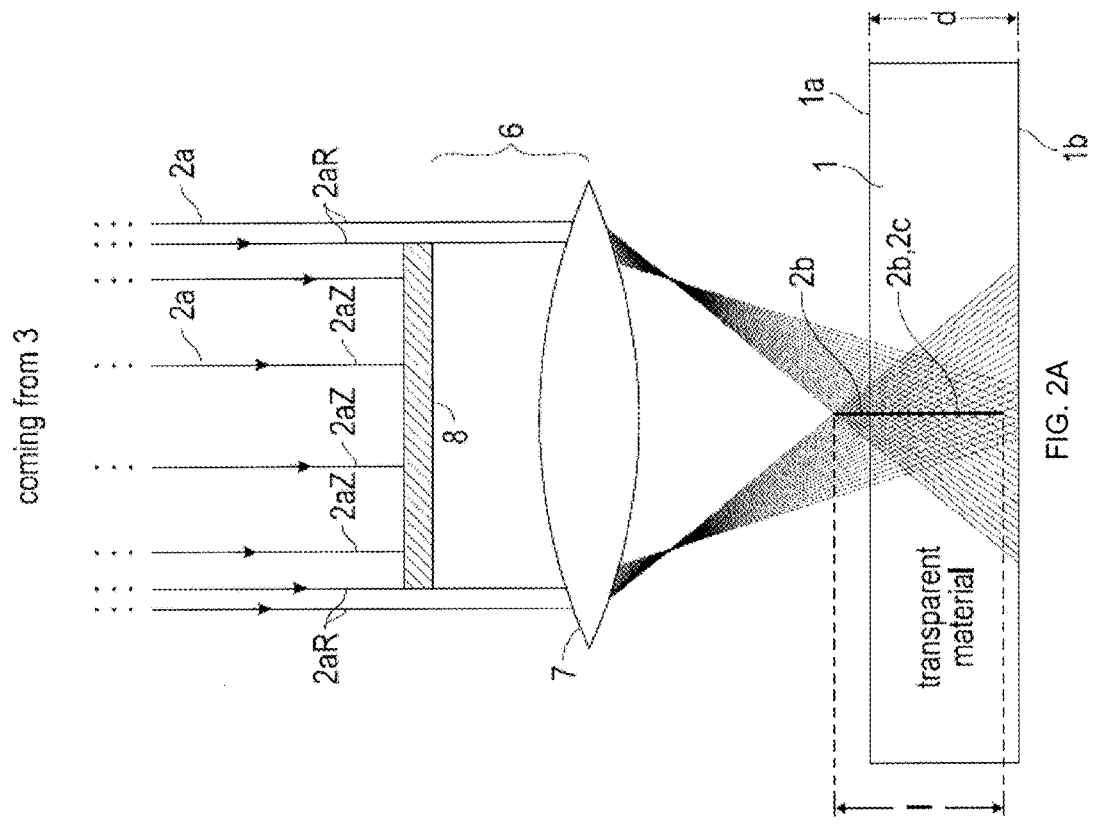


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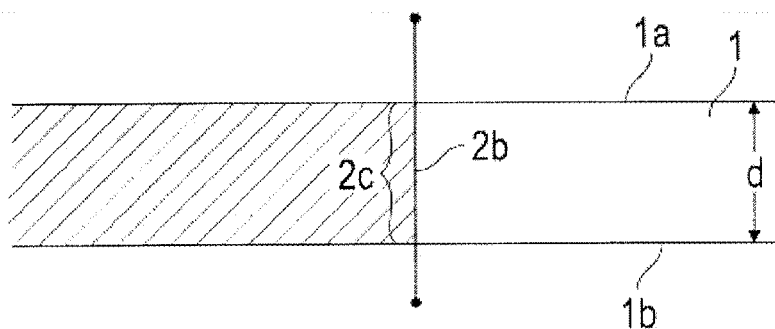


FIG. 2B-1

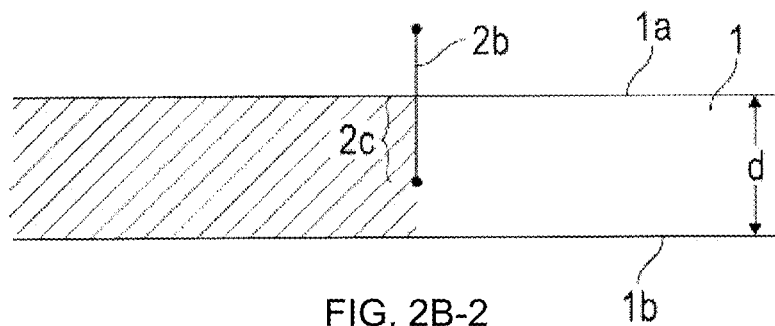


FIG. 2B-2

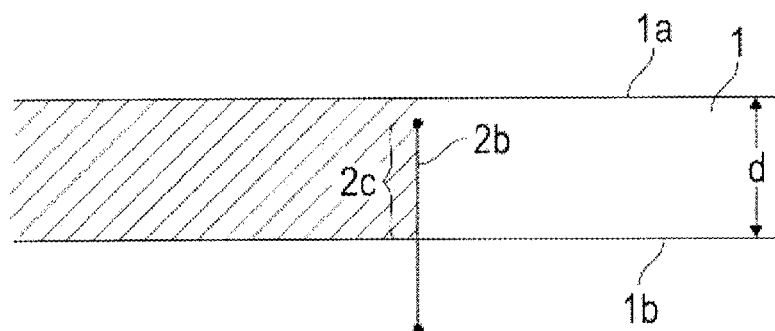


FIG. 2B-3

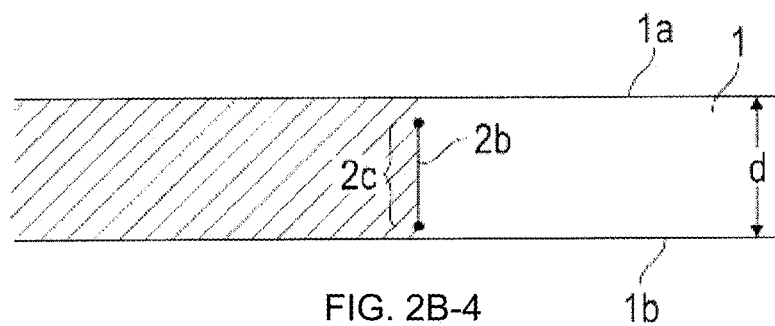


FIG. 2B-4

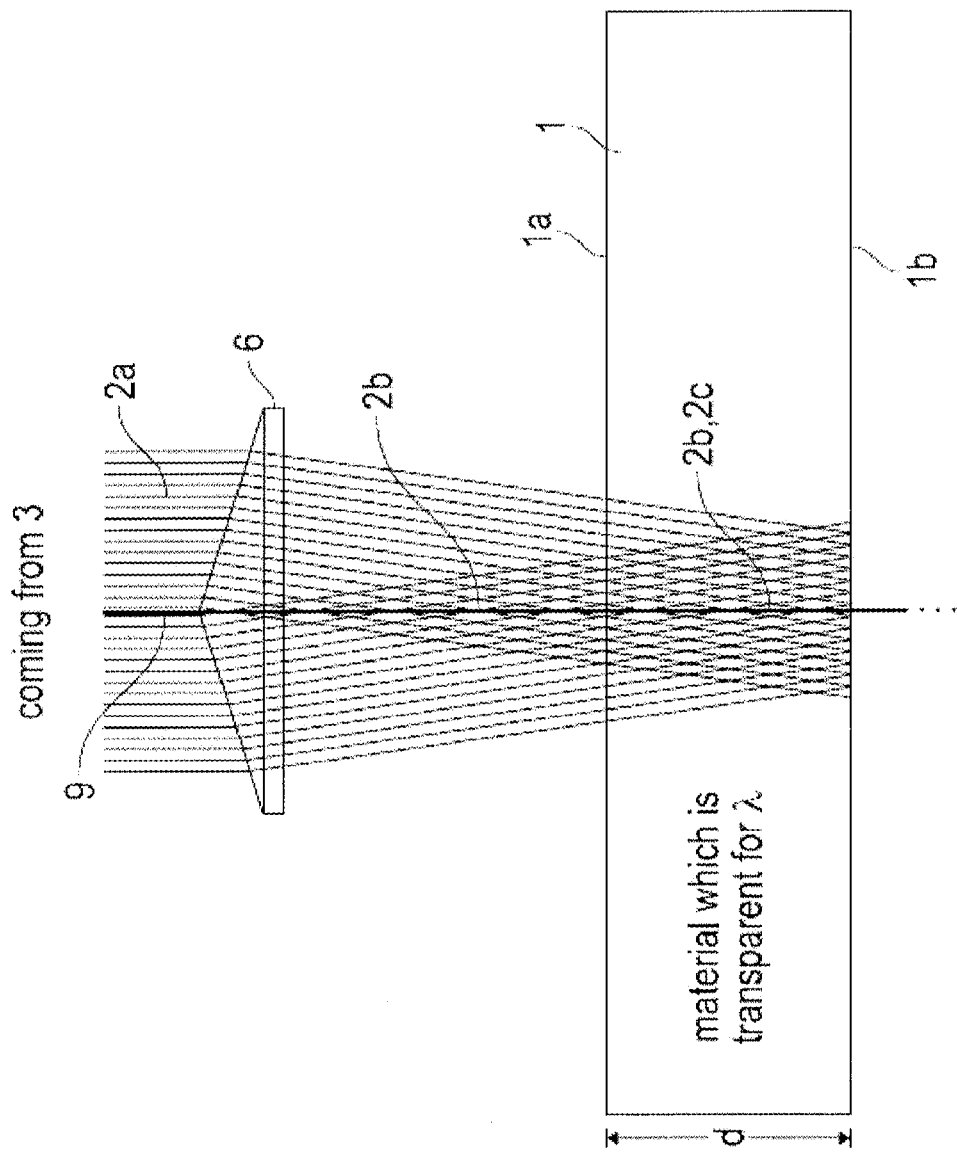
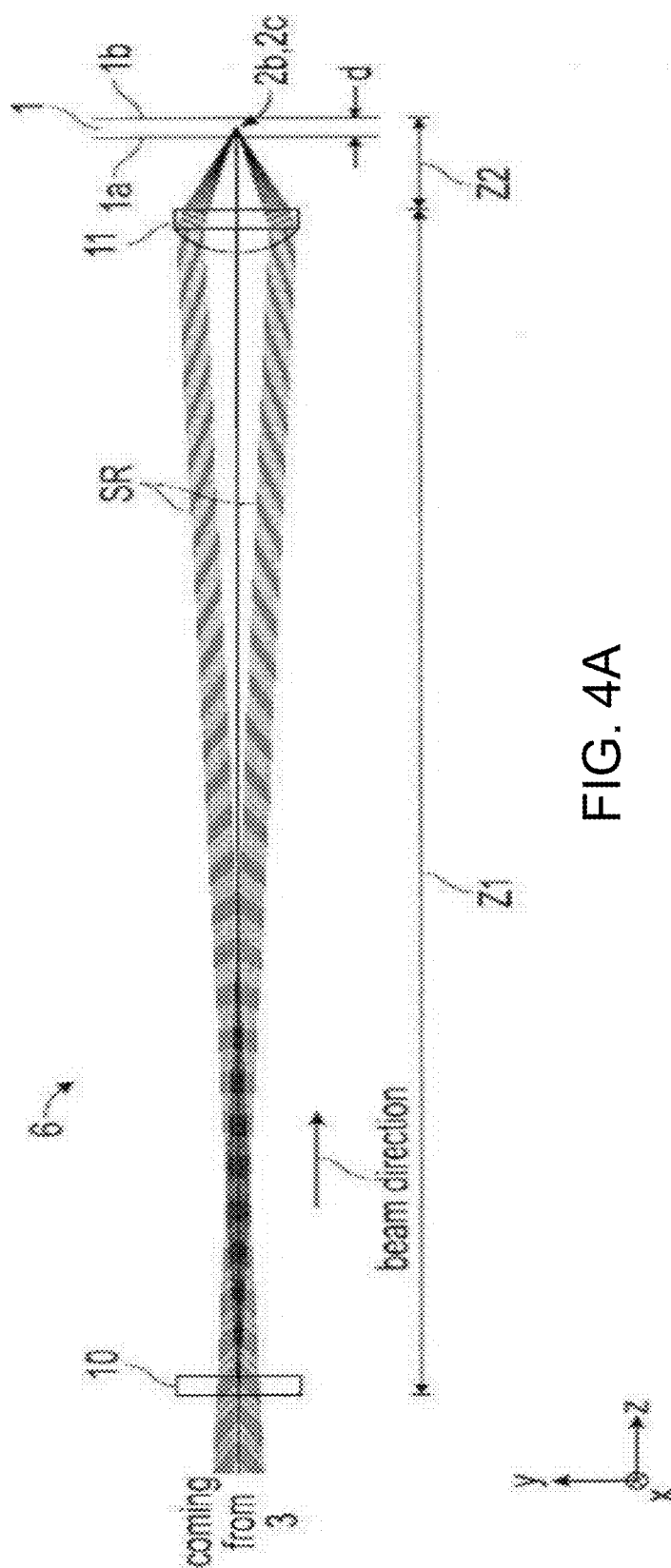
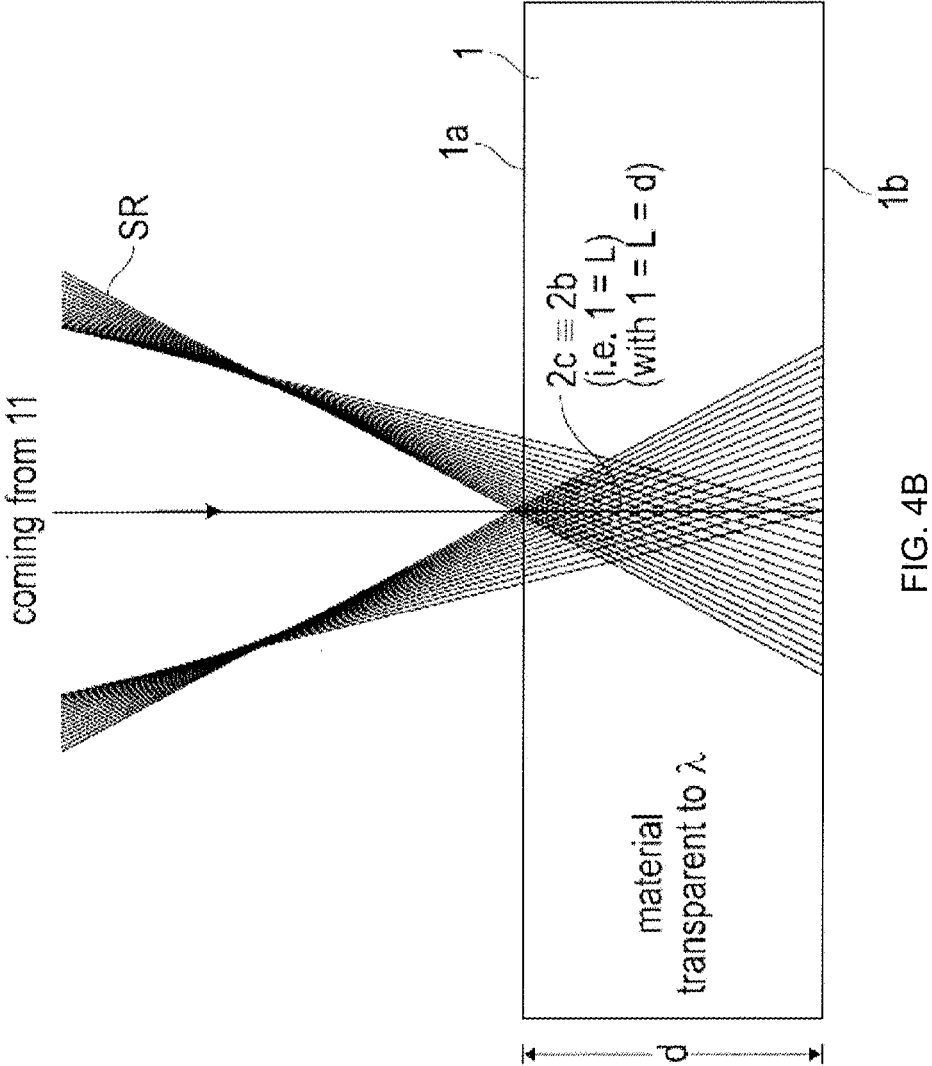


FIG. 3





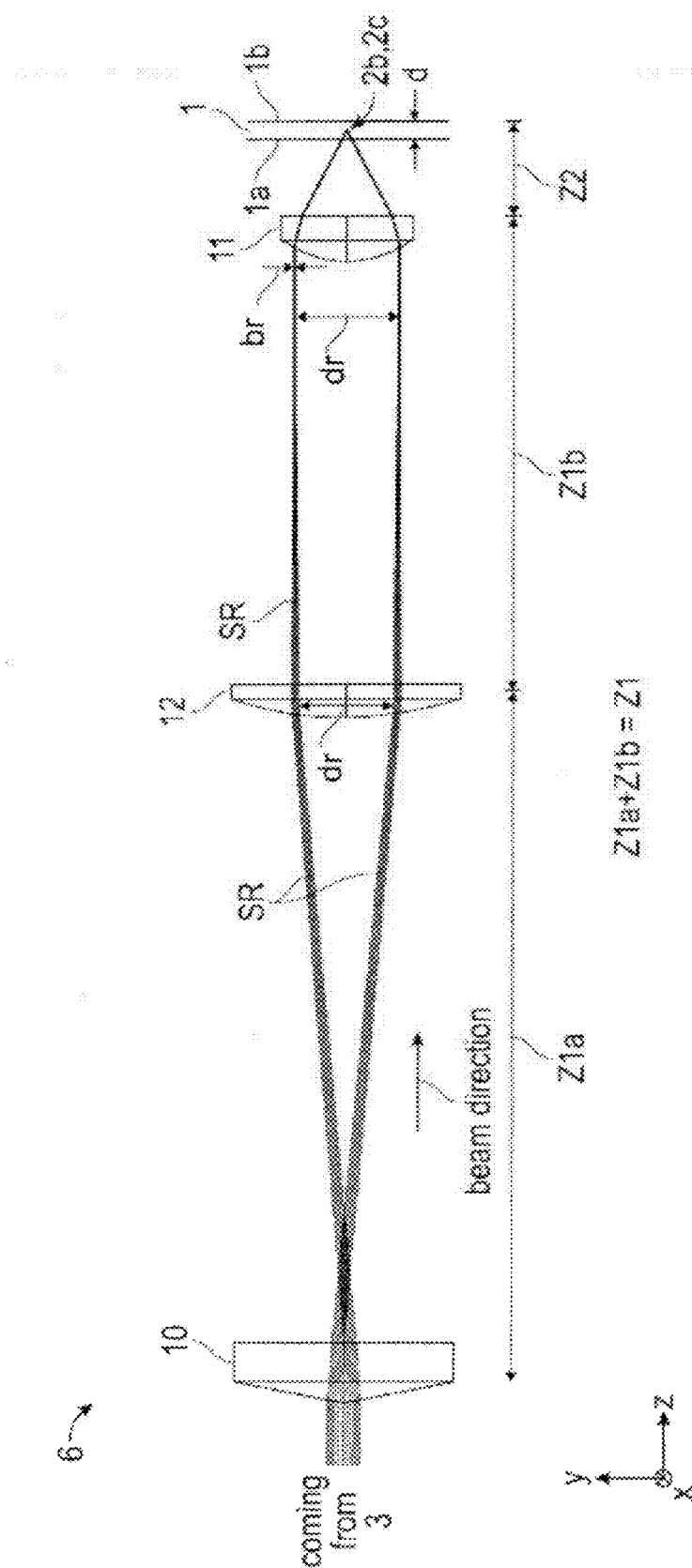


FIG. 5



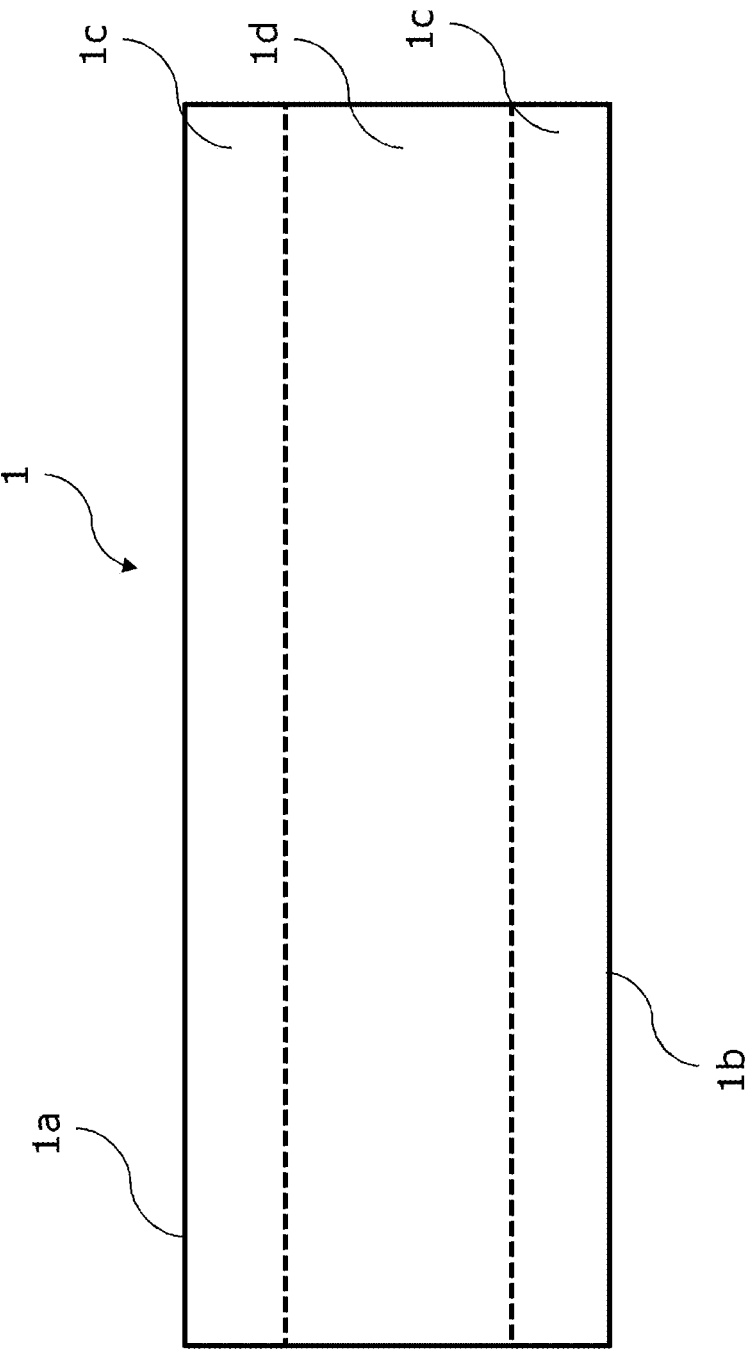


FIG. 6A

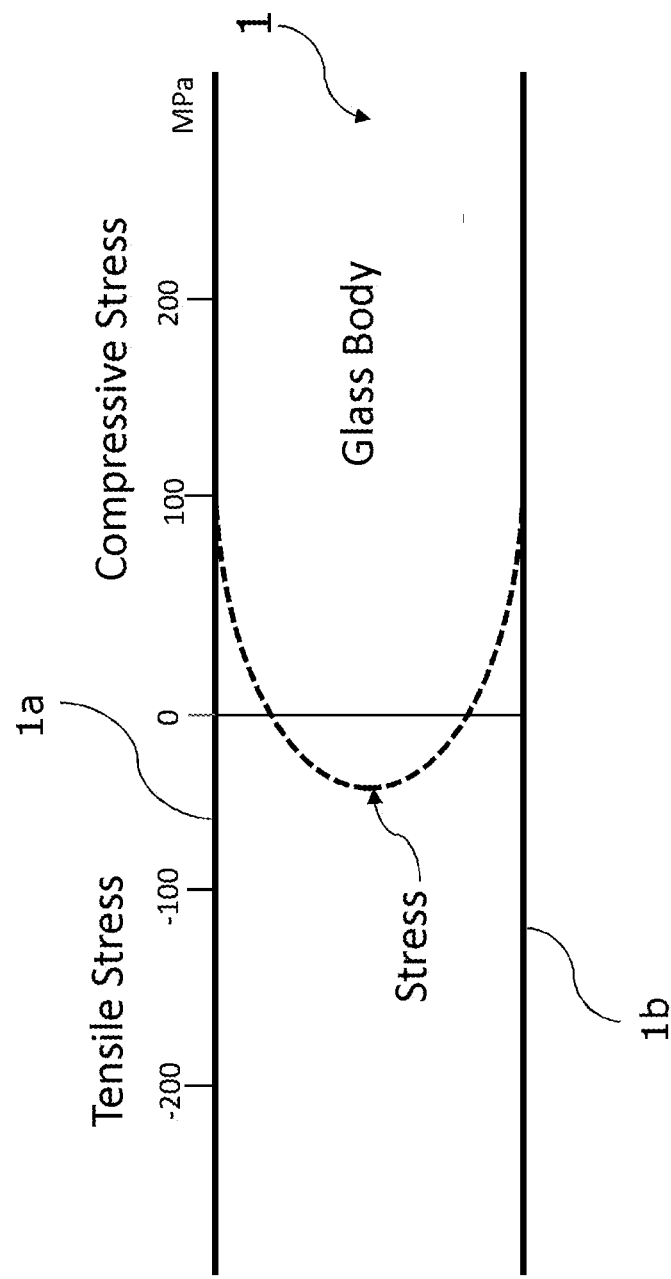


FIG. 6B

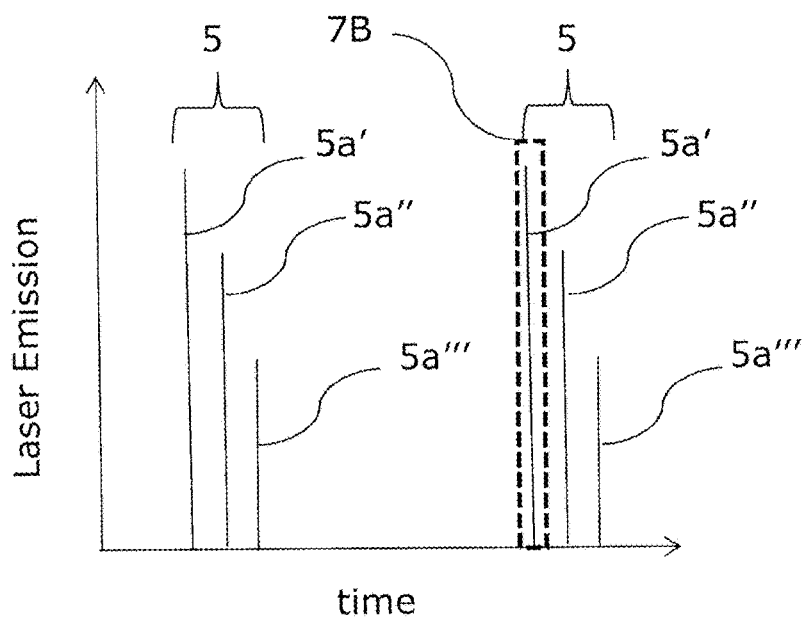


FIG. 7A

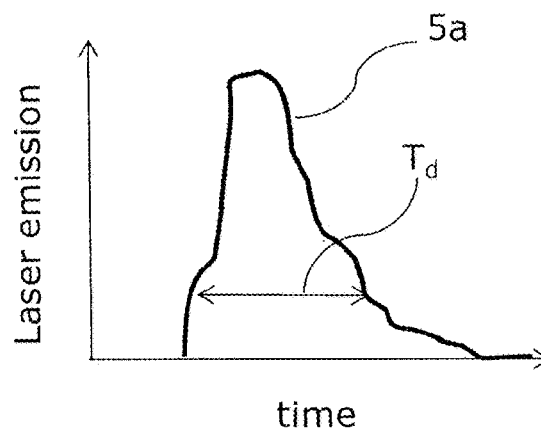


FIG. 7B

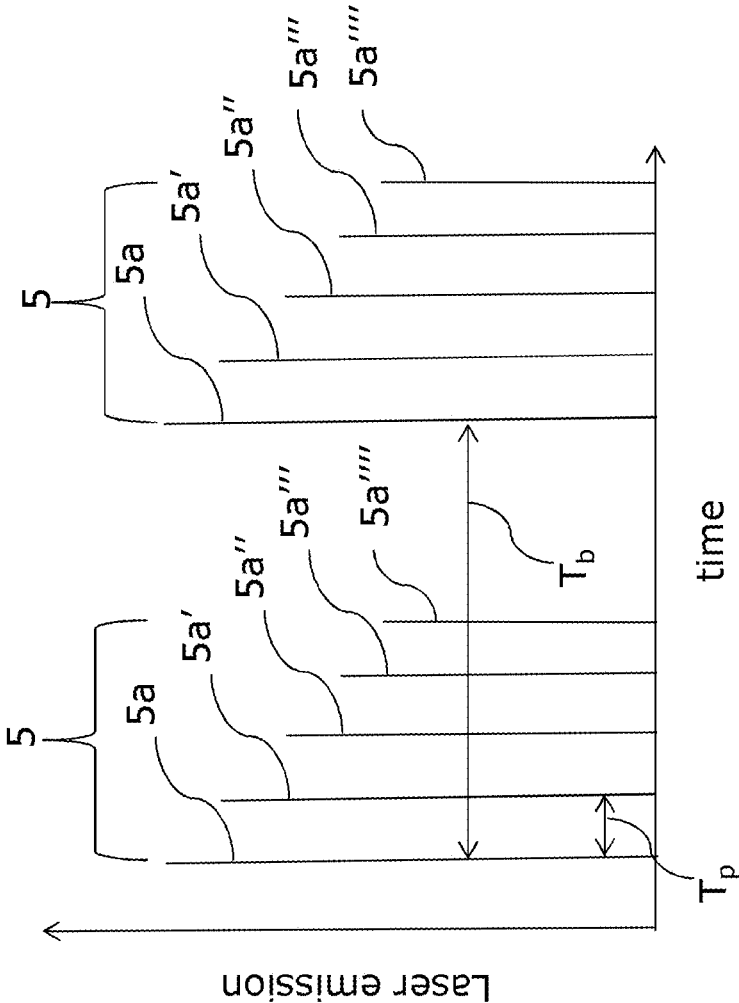


FIG. 7C

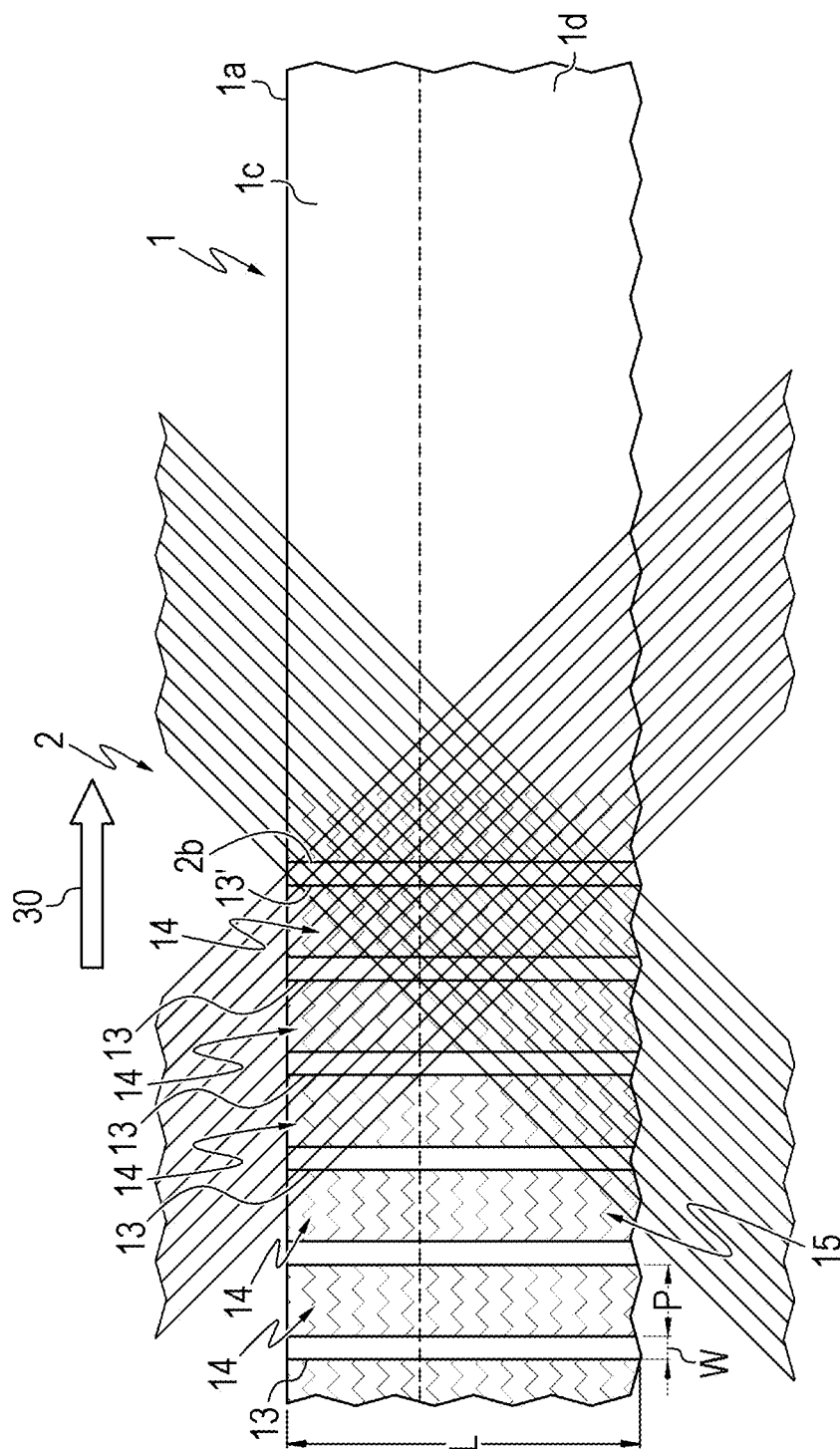


FIG. 8

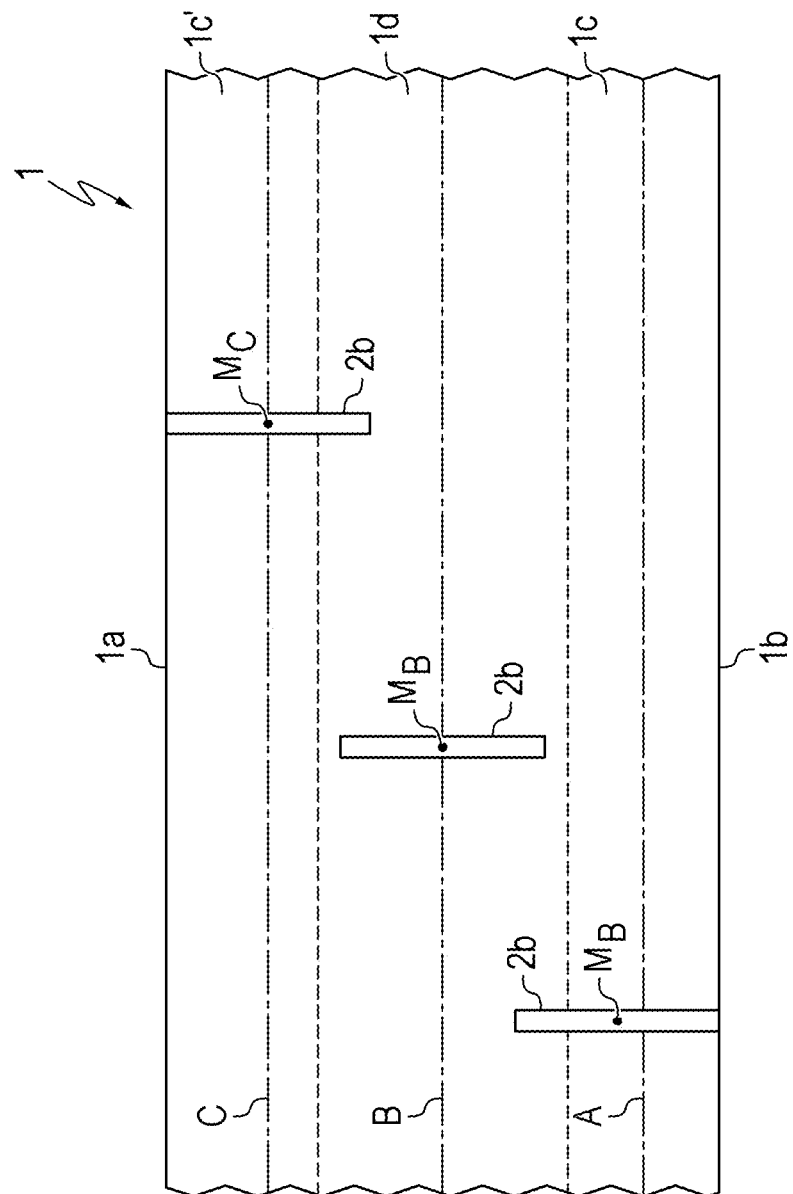


FIG. 9

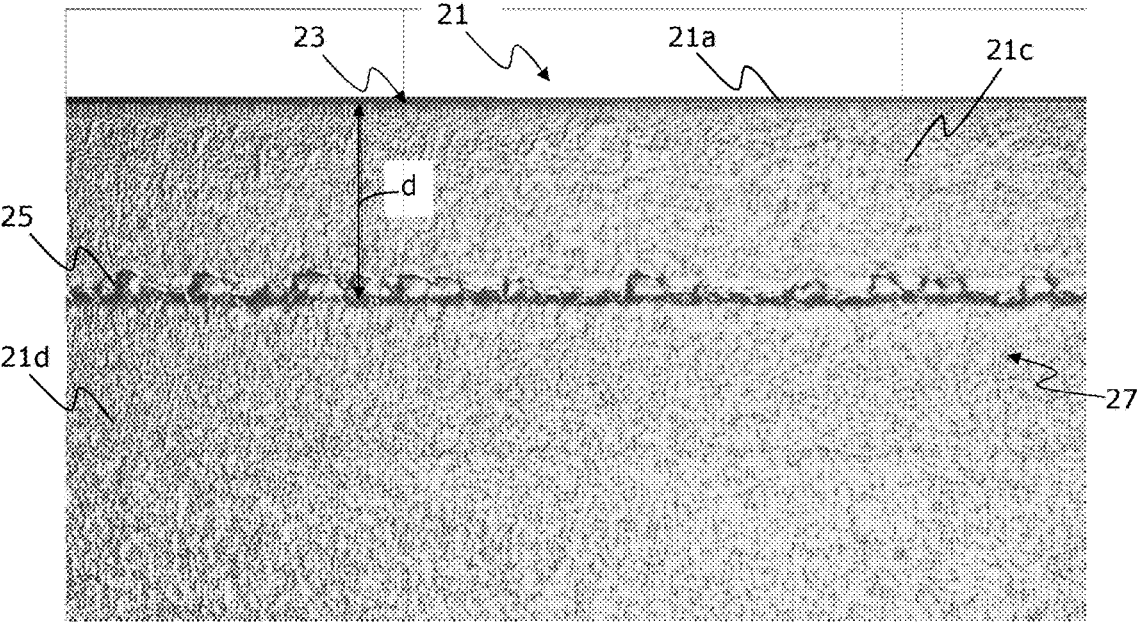


FIG. 10A

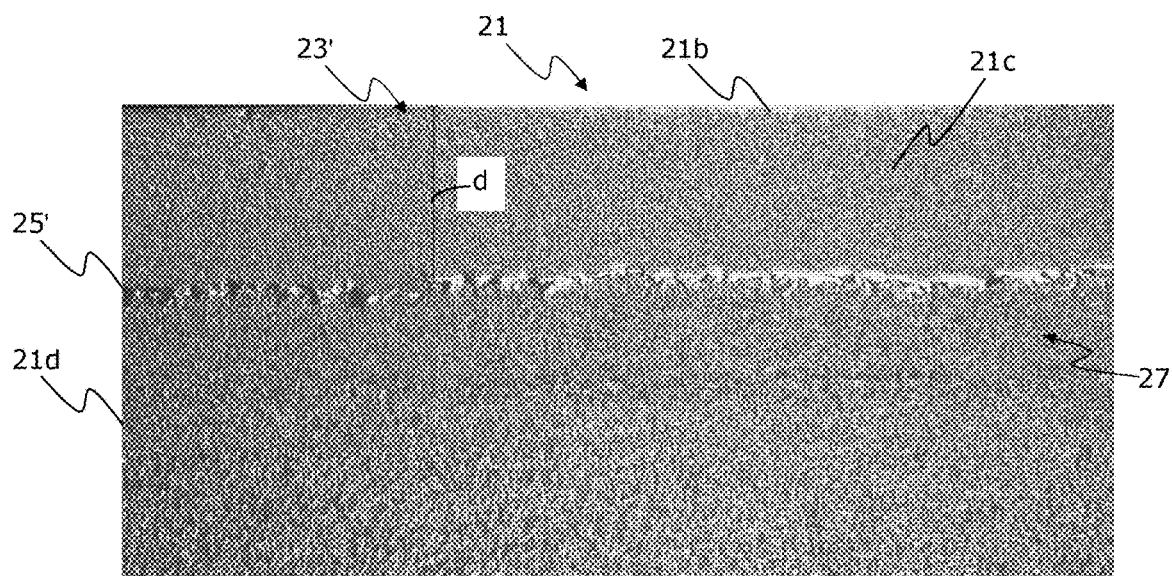


FIG. 10B



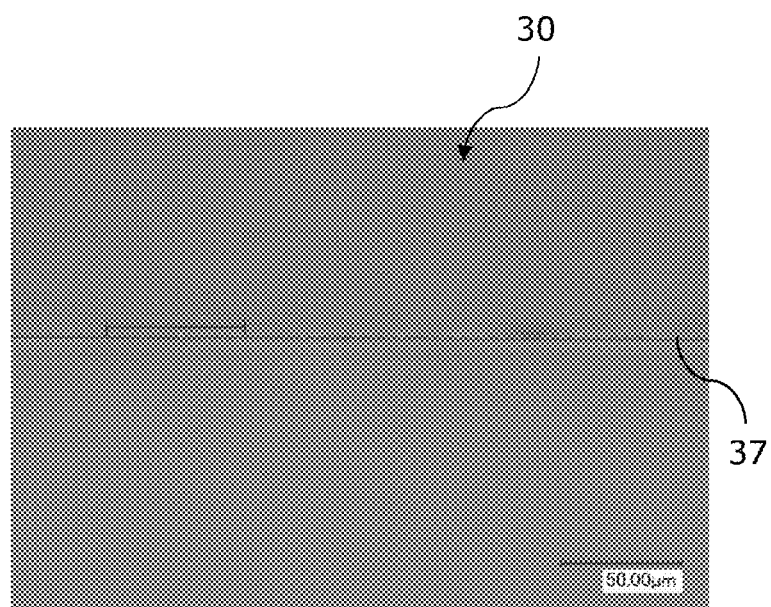


FIG. 11A

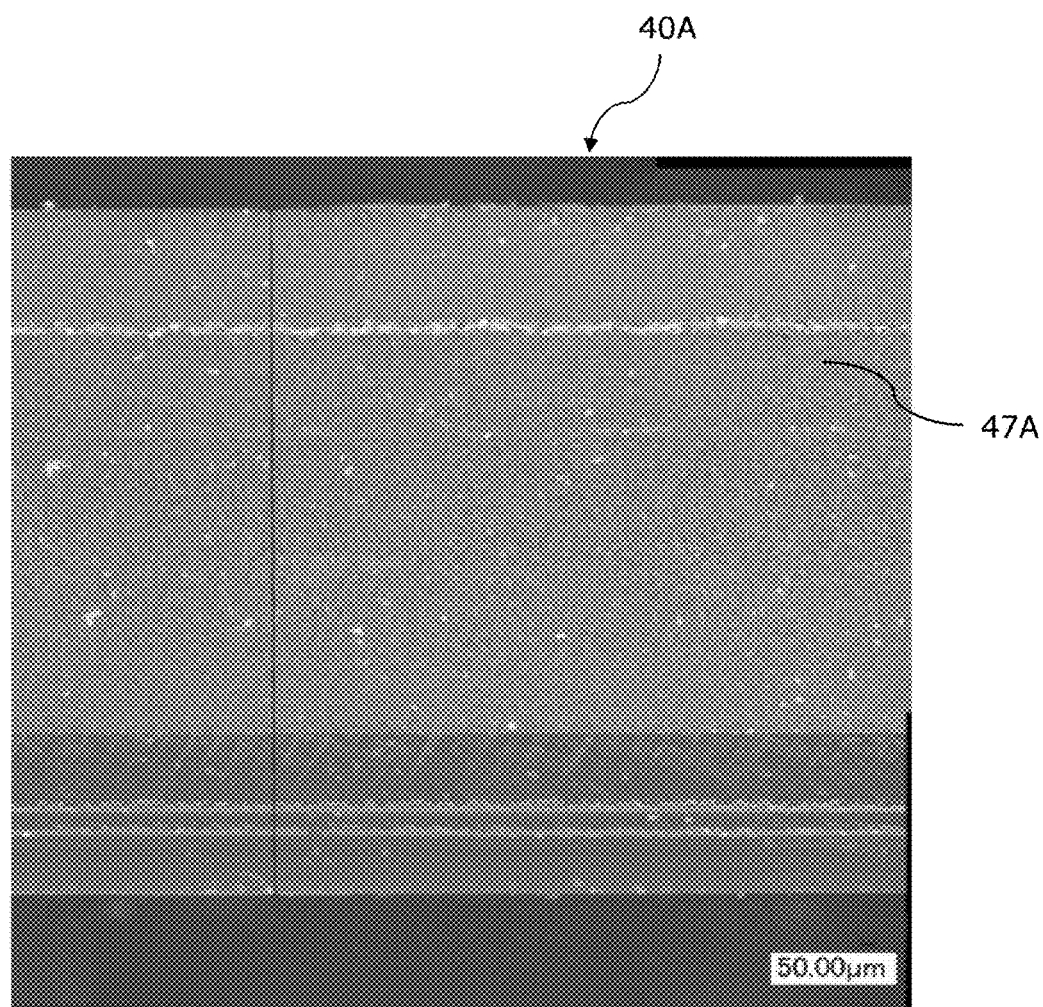


FIG. 12A

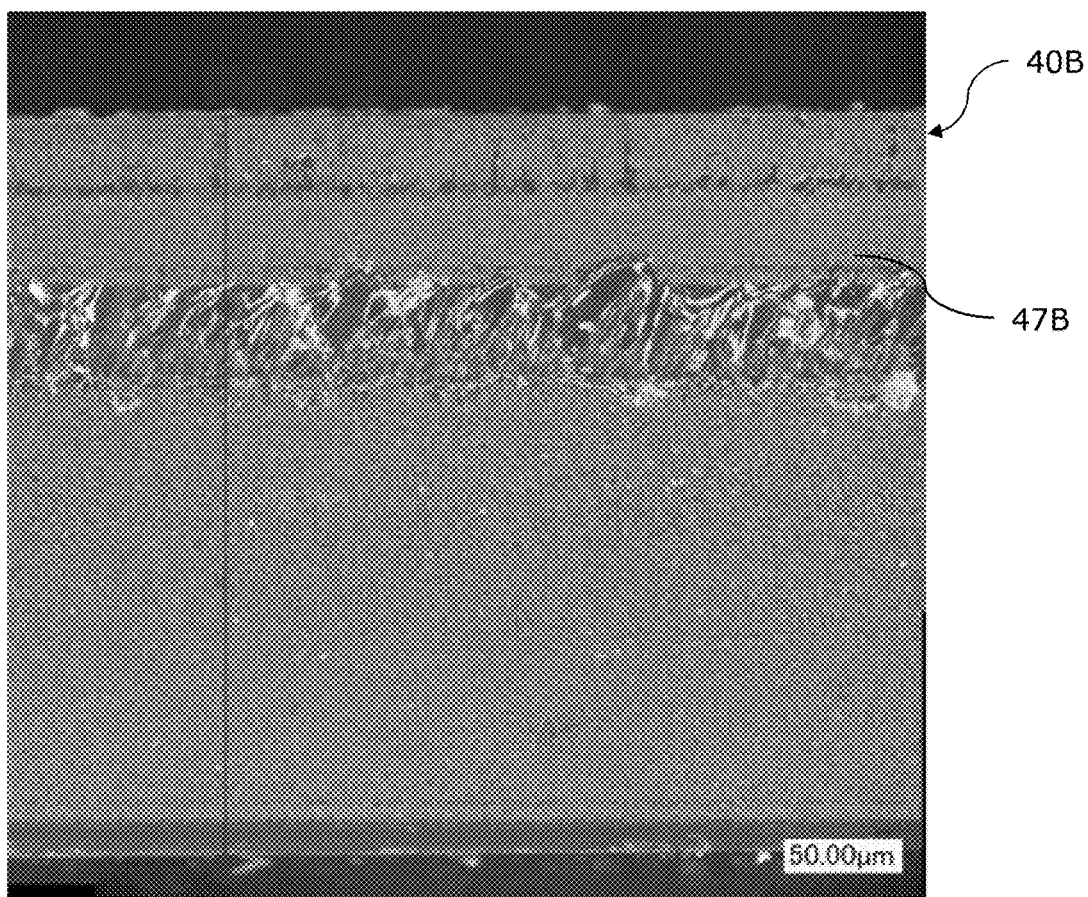


FIG. 12B

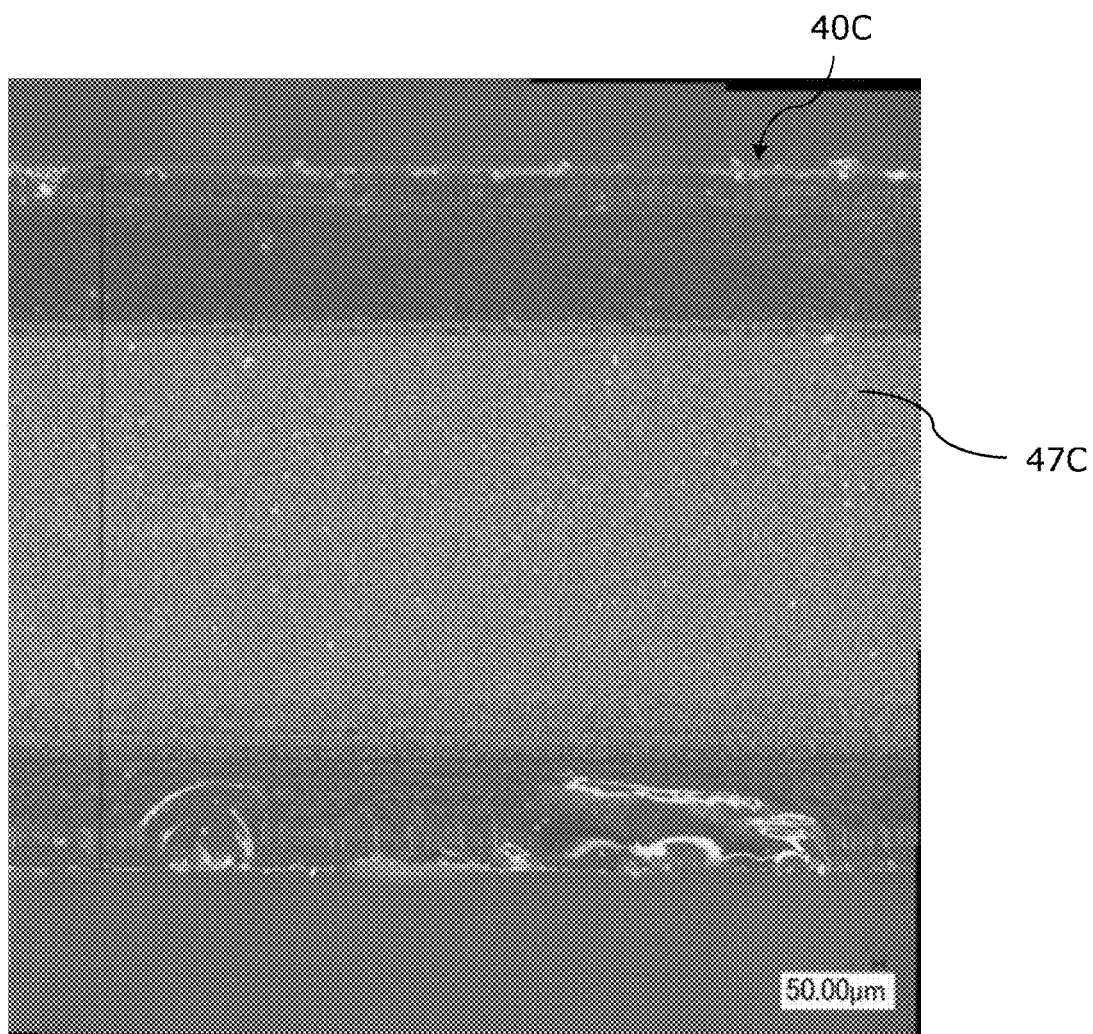


FIG. 12C

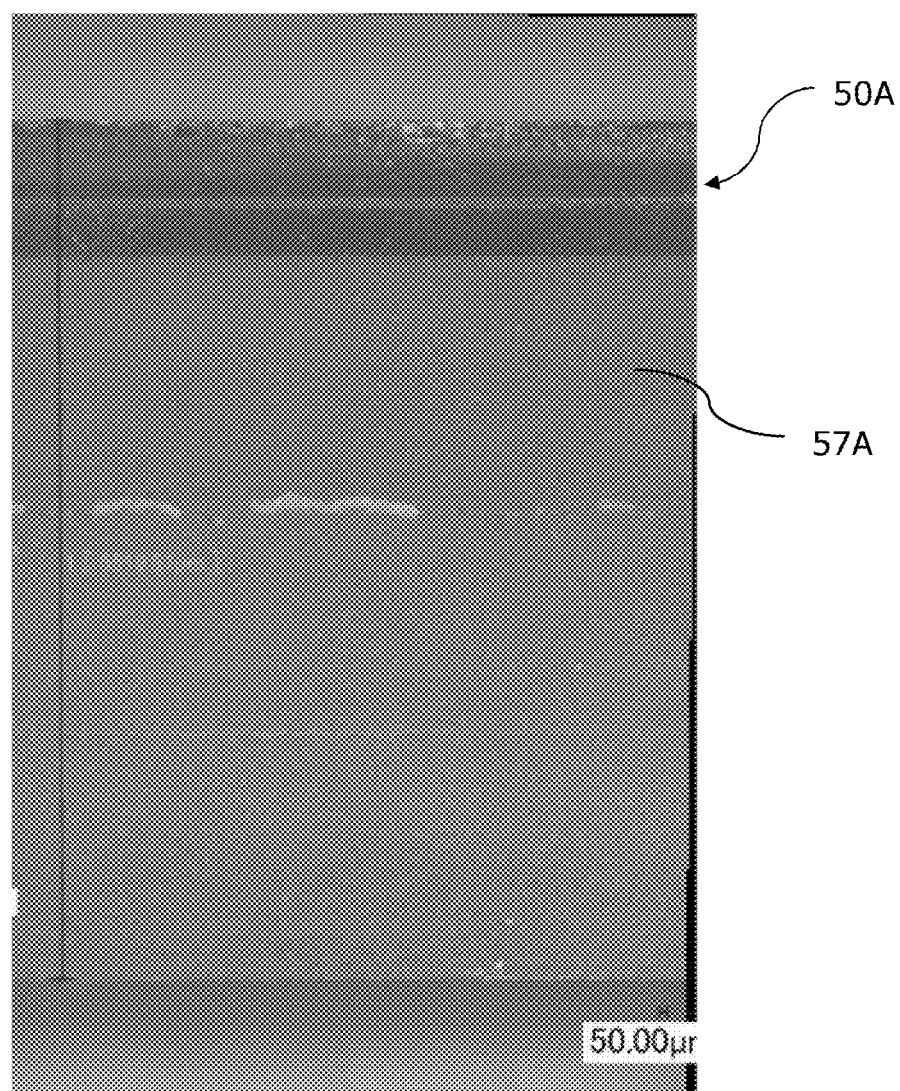


FIG. 13A

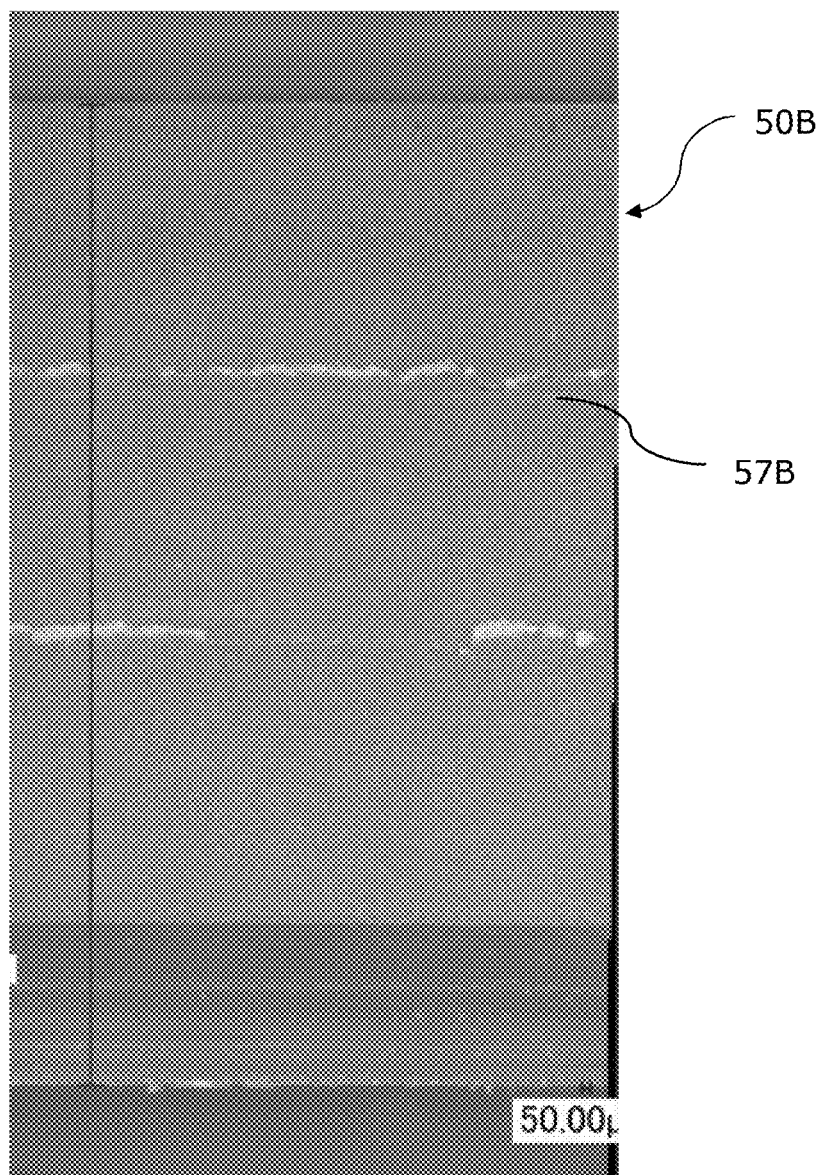


FIG. 13B

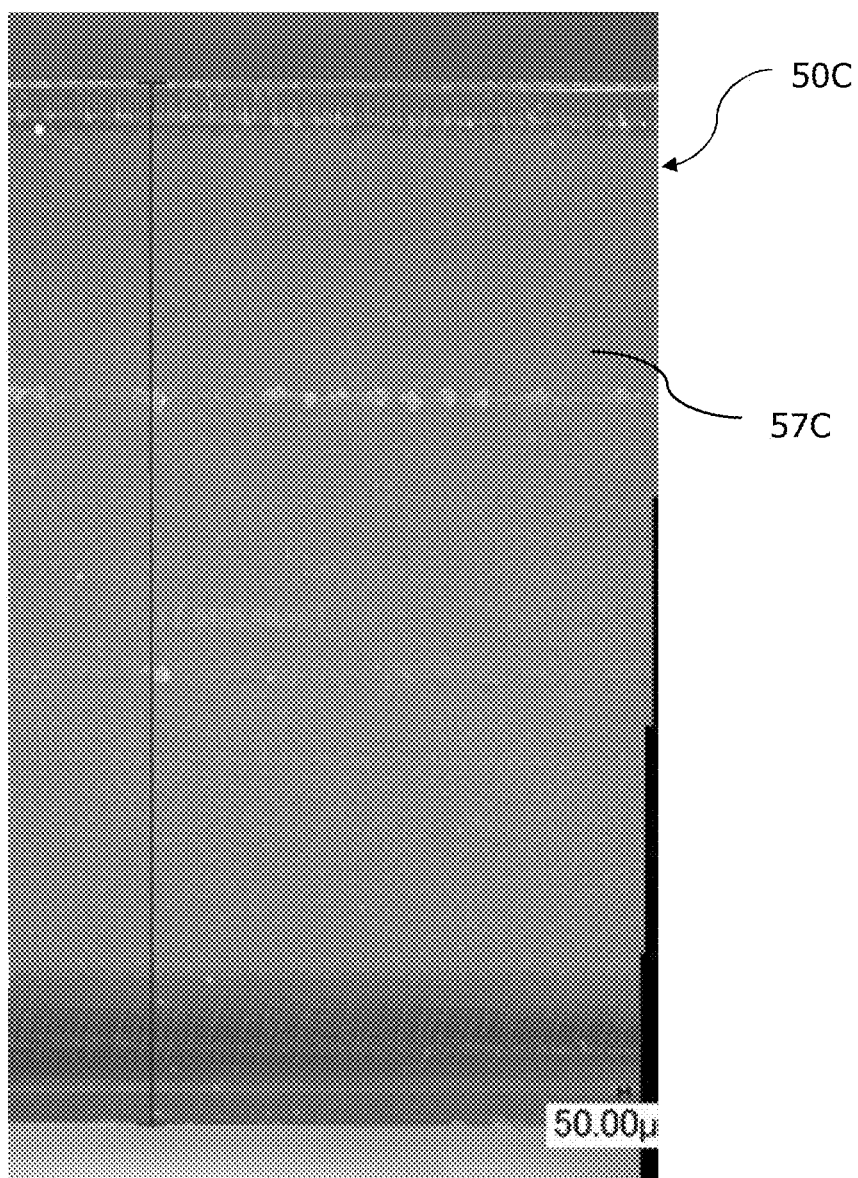


FIG. 13C

## LASER CUTTING OF THERMALLY TEMPERED SUBSTRATES

[0001] This application is a divisional of U.S. patent application Ser. No. 14/993,236 filed Jan. 12, 2016, which claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Ser. No. 62/102,257 filed on Jan. 12, 2015, the content of which is relied upon and incorporated herein by reference in its entirety.

### BACKGROUND

[0002] Thermally tempered substrates, such as thermally tempered glass, have a built-in stress profile that provides added strength and scratch resistance. Such substrates have found many applications, such as architectural glass applications and screens for electronic devices, for example.

[0003] In recent years, precision micromachining and its improvement of process development to meet customer demand to reduce the size, weight and material cost of leading-edge devices has led to fast pace growth in high-tech industries. Ultrafast industrial lasers are becoming important tools for applications requiring high precision micromachining.

[0004] However, due to the large amount of stress contained in thermally tempered glass, processing, such as cutting, is extremely difficult. Attempts at cutting thermally tempered glass with conventional methods releases this built-in stress and leads to fragmentation of the whole sheet. For this reason, thermally tempered glass is cut to shape before the thermal tempering process. Thus, thermally tempered glass sheets are only available in limited number of stock sizes. This may inhibit flexibility, impact the cost of custom fit sheets, and further limit use of tempered glass.

[0005] Accordingly, alternative systems and methods for cutting thermally tempered substrates may be desired.

### SUMMARY

[0006] In one embodiment, a method of separating a thermally tempered substrate includes directing a laser beam focal line into the thermally tempered substrate such that at least a portion of the laser beam focal line is within a bulk of the thermally tempered substrate. The laser beam focal line is formed by a focused pulsed laser beam, and the laser beam focal line is disposed along a beam propagation direction. The method further includes pulsing the focused pulsed laser beam to form a first sequence of pulse bursts comprising one or more sub-pulses. The laser beam focal line generates an induced multi-photon absorption within the thermally tempered substrate that produces a damage track within the bulk of the thermally tempered substrate along the laser beam focal line. The method further includes providing relative motion between the focused pulsed laser beam and the thermally tempered substrate in a first laser beam pass such that the pulsed laser beam forms a first sequence of damage tracks within the thermally tempered substrate. Individual damage tracks of the first sequence of damage tracks are separated by a lateral spacing, and one or more microcracks connect adjacent damage tracks of the first sequence of damage tracks.

[0007] In another embodiment, a system for processing a thermally tempered substrate includes a laser source operable to emit a pulsed laser beam, a translation table operable to be translated along at least one axis and operable to receive the thermally tempered substrate; and an optical

assembly disposed within an optical path of the pulsed laser beam. The optical assembly transforms the pulsed laser beam into a laser beam focal line, wherein at least a portion of the laser beam focal line is operable to be positioned within a bulk of the thermally tempered substrate such that the laser beam focal line generates an induced multi-photon absorption within the thermally tempered substrate to produce a material modification within the thermally tempered substrate along the laser beam focal line. The system further includes one or more controllers programmed to pulse the pulsed laser beam to form a sequence of pulse bursts comprising one or more sub-pulses, and to control the translation table to provide relative motion between the pulsed laser beam and the thermally tempered substrate along the at least one axis in a first laser beam pass such that the pulsed laser beam forms a sequence of damage tracks within the thermally tempered substrate. Individual damage tracks of the sequence of damage tracks are separated by a lateral spacing, and one or more microcracks extend between adjacent damage tracks of the sequence of damage tracks.

[0008] In yet another embodiment, a thermally tempered glass substrate includes a first surface and a second surface, wherein the first surface and the second surface have a compressive stress greater than or equal to 24 MPa, and a stress profile within a body of the thermally tempered glass substrate between the first and second surface is parabolic. The thermally tempered glass substrate further includes an edge extending from the first surface to the second surface, and a plurality of damage tracks positioned at the edge. Each individual damage track of the plurality of damage tracks has a diameter of less than or equal to 5  $\mu\text{m}$  and has a length of greater than or equal to 250  $\mu\text{m}$ . Adjacent damage tracks of the plurality of damage tracks are separated by a lateral spacing between about 2  $\mu\text{m}$  and about 20  $\mu\text{m}$ , and the plurality of damage tracks extend 50% or more of a length of the edge.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The foregoing will be apparent from the following more particular description of the example embodiments, 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 the representative embodiments.

[0010] FIGS. 1A and 1B are schematic illustrations of positioning the laser beam focal line in a thermally tempered substrate to form a damage track by induced absorption along the focal line according to one or more embodiments described and illustrated herein;

[0011] FIG. 2A is a schematic illustration of an optical assembly for laser processing according to one or more embodiments described and illustrated herein;

[0012] FIG. 2B-1 through 2B-4 are schematic illustrations of various possibilities to process the substrate by forming the laser beam focal line at different positions within the transparent material relative to the substrate according to one or more embodiments described and illustrated herein;

[0013] FIG. 3 is a schematic illustration of a second optical assembly for laser processing according to one or more embodiments described and illustrated herein;



**[0014]** FIGS. 4A and 4B are schematic illustrations of a third optical assembly for laser processing according to one or more embodiments described and illustrated herein;

**[0015]** FIG. 5 is a schematic illustration of a fourth optical assembly for laser processing;

**[0016]** FIGS. 6A and 6B are schematic illustrations of a thermally tempered substrate having two compressive regions and an inner tension region according to one or more embodiments described and illustrated herein;

**[0017]** FIG. 7A-7C are a graphs of example laser emission as a function of time for a picosecond laser according to one or more embodiments described and illustrated herein;

**[0018]** FIG. 8 schematically depicts a laser process to form a sequence of damage tracks within a thermally tempered substrate according to one or more embodiments described and illustrated herein;

**[0019]** FIG. 9 schematically depicts the laser line focus location within a thermally tempered substrate for three laser passes according to one or more embodiments described and illustrated herein;

**[0020]** FIG. 10A is a microscope image of a side (cross-section) of a laser-cut edge of a thermally tempered glass substrate at a laser-entrance surface;

**[0021]** FIG. 10B is a microscope image of a side (cross-section) of a laser-cut edge at a laser-exit surface of the thermally tempered glass substrate depicted in FIG. 10A;

**[0022]** FIG. 11A is a microscope image of a top side of laser-cut edge of a thermally tempered glass substrate;

**[0023]** FIGS. 12A-12C are microscope images of sides (cross sections) of a laser cut edges for three pieces of 3.2 mm thick thermally tempered glass substrate; and

**[0024]** FIGS. 13A-13C are microscope images of the sides (cross sections) of a laser cut edges for three pieces of 5.5 mm thick thermally tempered glass substrate.

#### DETAILED DESCRIPTION

**[0025]** Embodiments described herein relate to methods and systems for optically cutting thermally tempered substrates, such as thermally tempered glass materials. Generally, a laser beam is transformed to a laser beam focus line that is positioned within the bulk of a thermally tempered substrate, such as thermally tempered glass, to create one or more damage lines formed by damage tracks within the material. The thermally tempered substrate is separated along these damage lines.

**[0026]** Generally, a series of damage tracks can be made at extremely fast rates, with translation speeds that can exceed 1 m/s. With highly stressed glass, as is the case for thermally tempered glass, microcracks (or a single microcrack) will form and propagate extremely quickly once a damage site is created. This creates a considerable challenge in cutting high central tension glass, as microcracks can form and propagate faster than many laser methods can create suitable damage sites to guide the crack front. This leads to a loss of control of the crack. However, the methods disclosed herein can form a complete damage track with a single laser pulse or burst pulse, and therefore easily create the damage track locations at a speed which exceeds the speed at which the microcracks propagate, ensuring that the microcracks are directed from damage track to damage track, rather than running "out ahead" of the laser damage.

**[0027]** Thermally tempered glass may be created by using a controlled thermal treatment to increase the strength of the glass. The glass is heated in a high temperature oven (~600°

C.) and then its temperature rapidly lowered, for example by subjecting the glass to a cold air stream. This forces the outer layer of the glass to contract rapidly compared to the inner layers, which locks in high levels of compressive stress in the outer layers of the glass, while the inner layers of the glass are forced into tension to maintain a balance of forces inside the material. Fully tempered glass is generally defined as glass having a surface compressive stress of greater than 10,000 psi (69 MPa), and heat-strengthened glass is generally defined as glass having a surface compressive stress of greater than 3,500 psi (24 MPa).

**[0028]** The stress profile as a function of depth for thermal tempering is generally parabolic and slowly changing with depth, whereas with chemical strengthened glass (e.g., ion exchanged chemically strengthened glass) where the stress profile is more exponential with depth and confined to a region close to the glass surface. The compressive stress layer for thermally tempered glass is thus often much deeper, often >>100  $\mu\text{m}$  for thermal tempering, but generally <100  $\mu\text{m}$  for chemical strengthening. In addition, thermal tempering is generally limited to glass pieces of thickness >2 mm, and mostly >3 mm, whereas chemical strengthening is frequently confined to thinner glass pieces.

**[0029]** Such stress distribution and deep compressive stress layer makes the thermally tempered glass extremely resistant to breakage from surface impact. When the glass does break, it generally fractures into fragments which are not sharp.

**[0030]** At present, any cutting of thermally tempered glass involves special treatment of the glass first to effectively de-temper it. One method creates bands of un-tempered glass by heating the material locally around the desired shapes to be separated from a larger thermally tempered sheet. Then the glass is cut along the un-tempered bands so that the actual tempered portion of the sheet is surrounded by un-tempered (annealed) glass which is then finished

**[0031]** Thermally tempered glass is in great demand where glass strength is desired. It is used in most modern architectural glass facades, in passenger vehicle windows, in shower doors, and a wide variety of consumer applications. In addition, thermally tempered soda-lime glass can be used in conjunction with higher quality display glasses such as alkaline boro-aluminosilicate glass (e.g., Corning® Eagle XG' glass) to fabricate electrochromically controlled windows. The use of the higher quality display glasses (flatter, more compositional uniformity, low alkali content) for some of the portions of the window glass may stack lead to better electrical performance and higher yields when electrochromic electronic layers are applied. The ability cut both materials into complex shapes is of significant interest because it enables higher material (sheet) utilization. Electrochromic layers are applied and patterned on the glass, but must be applied after any thermal tempering, due to the high temperatures involved in tempering. If the thermally tempered glass can be cut after it is patterned with electrochromic layers, then greater process flexibility can be realized by using common equipment for coating and tempering, and then simply cutting the parts to shape downstream.

**[0032]** As stated above, embodiments of the present disclosure are directed to systems and methods for laser cutting thermally tempered glass without the need for de-tempering. Embodiments utilize an ultra-short pulsed laser and a specialized optical delivery system to create precise perforations (i.e., damage tracks) within the thermally tempered

glass. These perforations or damage tracks allow any crack propagation to be precisely controlled, preventing the glass sheet from shattering during the cutting process.

**[0033]** In accordance with methods described below, a laser can be used to create highly controlled full line perforation through a thermally tempered (i.e., strengthened) material, with extremely little ( $<75\ \mu\text{m}$ , often  $<50\ \mu\text{m}$ ) subsurface damage and negligible debris generation. Thus, it is possible to create a microscopic (i.e.,  $<0.5\ \mu\text{m}$  and  $>100\ \text{nm}$  in diameter) elongated “hole” or void (also referred to as a perforation, defect line, or damage track herein) in transparent, thermally tempered material using a single high energy pulse or burst pulse. These individual damage tracks (or “perforations”) can be created at rates of several hundred kilohertz (several hundred thousand perforations per second, for example). Thus, with relative motion between the source and the material these perforations can be placed adjacent to one another (spatial separation varying from sub-micron to tens of microns as desired). This spatial separation is selected in order to facilitate cutting. In some embodiments, the damage track is a “through hole”, which is a hole or an open channel that extends from the top to the bottom of the transparent material. In some embodiments, the damage track may not be a continuous channel, and may be blocked or partially blocked by portions or sections of solid material (e.g., glass). As defined herein, the internal diameter of the damage track is the internal diameter of the open channel or the air hole or void in the material. For example, in the embodiments described herein the internal diameter of the damage track is  $<500\ \text{nm}$ , for example  $\leq 400\ \text{nm}$ , or  $\leq 300\ \text{nm}$ .

**[0034]** As described in more detail below, the damage tracks formed by each laser pulse (or burst of sub-pulses) extend through the compressive layer(s) in into a tension region of the thermally tempered substrate. Unlike other laser methods, this method does not require a long dwell multiple-pulse or percussion drilling approach to drill a hole all the way through the material.

**[0035]** Because thermally tempered glass contains a high level of internal stress, microcracks will emerge from these damaged locations. However, they will preferentially be guided from one damage track to another, as long as the damage track sites are closely spaced and are formed faster than the speed of microcrack propagation. The propagation of these microcracks will then separate the glass along the desired perforated contour, as described in detail below.

**[0036]** The wavelength of the laser is selected so that the material to be laser processed (drilled, cut, ablated, damaged or otherwise appreciably modified by the laser) is transparent to the laser wavelength. In one embodiment, the material to be processed by the laser is transparent to the laser wavelength if it absorbs less than 10% of the intensity of the laser wavelength per mm of thickness of the material. In another embodiment, the material to be processed by the laser is transparent to the laser wavelength if it absorbs less than 5% of the intensity of the laser wavelength per mm of thickness of the material. In still another, the material to be processed by the laser is transparent to the laser wavelength if it absorbs less than 2% of the intensity of the laser wavelength per mm of thickness of the material. In yet another embodiment, the material to be processed by the laser is transparent to the laser wavelength if it absorbs less than 1% of the intensity of the laser wavelength per mm of thickness of the material.

**[0037]** The selection of the laser source is further predicated on the ability to induce multi-photon absorption (MPA) in the transparent material. MPA is the simultaneous absorption of multiple photons (e.g. two, three, four or more) of identical or different frequencies in order to excite a material from a lower energy state (usually the ground state) to a higher energy state (excited state). The excited state may be an excited electronic state or an ionized state. The energy difference between the higher and lower energy states of the material is equal to the sum of the energies of the two or more photons. MPA is a nonlinear process that is several orders of magnitude weaker than linear absorption. In the case of two-photon absorption, it differs from linear absorption in that the strength of absorption depends on the square of the light intensity, thus making it a nonlinear optical process. At ordinary light intensities, MPA is negligible. If the light intensity (energy density) is extremely high, such as in the region of focus of a laser source (particularly a pulsed laser source), MPA becomes appreciable and leads to measurable effects in the material within the region where the energy density of the light source is sufficiently high. Within the focal region, the energy density may be sufficiently high to result in ionization, breaking of molecular bonds, and vaporization of material.

**[0038]** At the atomic level, the ionization of individual atoms has discrete energy requirements. Several elements commonly used in glass (e.g., Si, Na, K) have relatively low ionization energies ( $\sim 5\ \text{eV}$ ). Without the phenomenon of MPA, a wavelength of about  $248\ \text{nm}$  would be required to create linear ionization at  $\sim 5\ \text{eV}$ . With MPA, ionization or excitation between states separated in energy by  $\sim 5\ \text{eV}$  can be accomplished with wavelengths longer than  $248\ \text{nm}$ . For example, photons with a wavelength of  $532\ \text{nm}$  have an energy of  $\sim 2.33\ \text{eV}$ , so two photons with wavelength  $532\ \text{nm}$  can induce a transition between states separated in energy by  $\sim 4.66\ \text{eV}$  in two-photon absorption (TPA), for example.

**[0039]** Thus, atoms and bonds can be selectively excited or ionized in the regions of a material where the energy density of the laser beam is sufficiently high to induce nonlinear TPA of a laser wavelength having half the required excitation energy, for example. MPA can result in a local reconfiguration and separation of the excited atoms or bonds from adjacent atoms or bonds. The resulting modification in the bonding or configuration can result in non-thermal ablation and removal of matter from the region of the material in which MPA occurs. This removal of matter creates a structural defect (i.e., a perforation, defect line, or damage track) that mechanically weakens the material and renders it more susceptible to cracking or fracturing. By controlling the placement of damage tracks, a contour or path along which cracking occurs can be precisely defined to guide stress-induced microcracks between adjacent damage tracks. The contour defined by a series of damage tracks may be regarded as a fault line and corresponds to a region of structural weakness in the material.

**[0040]** Damage tracks can be accomplished with a single “burst” of high energy, short duration sub-pulses spaced close together in time. The laser pulse duration may be  $10^{-10}\ \text{s}$  or less, or  $10^{-11}\ \text{s}$  or less, or  $10^{-12}\ \text{s}$  or less, or  $10^{-13}\ \text{s}$  or less. These “bursts” may be repeated at high repetition rates (e.g. kHz or MHz). The damage tracks may be spaced apart and precisely positioned by controlling the velocity of a substrate or stack of substrates relative to the laser through control of the motion of the laser and/or the substrate. As an

example, in a thermally tempered substrate moving at 200 mm/sec exposed to a 100 kHz series of pulses, the individual pulses would be spaced 2 microns apart to create a series of damage tracks separated by 2 microns. In some embodiments, the thermally tempered substrate is positioned on a translation table (not shown) capable of being translated along at least one axis. Any translation table or other device capable of translating either the glass substrate or the optical delivery head may be utilized.

**[0041]** Turning to FIGS. 1A and 1B, a method of laser drilling a thermally tempered substrate includes focusing a pulsed laser beam 2 into a laser beam focal line 2b, viewed along the beam propagation direction. Laser beam focal line 2b is a region of high energy density. As shown in FIG. 2, laser 3 (not shown) emits laser beam 2, which has a portion 2a incident to 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 1 of the focal line).

**[0042]** Embodiments of the present disclosure utilize non-diffracting beams (“NDB”) to form the laser beam focal line 2b. Typically, laser processing has used Gaussian laser beams. The tight focus of a laser beam with a Gaussian intensity profile has a Rayleigh range ZR given by:

$$Z_R = \frac{\pi n_o w_o^2}{\lambda_o} \quad \text{Eq. (1)}$$

**[0043]** The Rayleigh range represents the distance over which the spot size  $w_o$  of the beam will increase by  $\sqrt{2}$  in a material of refractive index  $n_o$  at wavelength  $\lambda_o$ . This limitation is imposed by diffraction. Note in Eq. (1) that the Rayleigh range is related directly to the spot size, thereby leading to the conclusion that a beam with a tight focus (i.e. small spot size) cannot have a long Rayleigh range. Such a beam will maintain this small spot size only for a very short distance. This also means that if such a beam is used to drill through a material by changing the depth of the focal region, the rapid expansion of the spot on either side of the focus will require a large region free of optical distortion that might limit the focus properties of the beam. Such a short Rayleigh range also requires multiple pulses to cut through a thick sample.

**[0044]** However, embodiments of the present disclosure utilize NDBs instead of the optical Gaussian beams discussed above. Non-diffracting beams may propagate for a considerable distance before diffraction effects inevitably limit the beam focus. Although an infinite NDB does not suffer from diffractive effects, a physically realizable NDB will have a limited physical extent. The central lobe of the beam can be quite small in radius and thus produce a high intensity beam. There are several types of NDBs including, but not limited to, Bessel beams, Airy beams, Weber beams and Mathieu beams whose field profiles are typically given by special functions which decay more slowly in the transverse direction than a Gaussian function.

**[0045]** It should be understood that, although NDBs described are described herein in the context of Bessel beams, embodiments are not limited thereto. The central spot size of a Bessel beam is given by:

$$d = 2 \frac{2.405 \lambda_o}{NA \ 2\pi n_o}, \quad \text{Eq. (2)}$$

where NA is the numerical aperture given by the cone of plane waves making an angle of  $\beta$  with the optical axis. A key difference between Bessel beams and Gaussian beams is that Rayleigh range of a Bessel beam is given by:

$$Z_{max} = \frac{\pi D d}{4\lambda}, \quad \text{Eq. (3)}$$

where D is the finite extent of the beam imposed by some aperture or optical element. It is therefore shown that the aperture size D may be used to increase the Rayleigh range beyond the limit imposed by the size of the central spot. A practical method for generating Bessel beams is to pass a Gaussian beam through an axicon or an optical element with a radially linear phase gradient.

**[0046]** In general, the optical method of forming the line focus (i.e., the laser beam focal line) can take multiple forms, such as, without limitation, using donut shaped laser beams and spherical lenses, axicon lenses, diffractive elements, or other methods to form the linear region of high intensity. Various optical methods of forming and adjusting the line focus are described in U.S. Pat. Appl. No. 62/024, 122, which is incorporated by reference herein in its entirety. The type of laser (picosecond, femtosecond, and the like) and wavelength (IR, visible, UV, and the like) may also be varied, as long as sufficient optical intensities are reached to create breakdown of the substrate material.

**[0047]** The laser power and lens focal length (which determines the line focus length and hence power density) are parameters that ensure full penetration of the substrate for cutting. Accordingly, the dimensions of the line focus formed in the substrate should be controlled.

**[0048]** Referring once again to FIGS. 1A and 1B, a thermally tempered substrate 1 (e.g., thermally tempered glass) in which internal modifications by laser processing and multi-photon absorption is to occur is schematically illustrated. The thermally tempered substrate 1 may be disposed on a substrate or carrier. In some embodiments, multiple thermally tempered substrates 1 are arranged in a stack for simultaneous processing. The thermally tempered substrate 1 may be positioned on a translation table (not shown) configured to move along at least one axis. The translation table may be controlled by one or more controllers (not shown), for example. The thermally tempered substrate 1 is positioned in the beam path to at least partially overlap the laser beam focal line 2b of laser beam 2. The laser beam 2 may be generated by a laser source (not shown), which may be controlled by one or more controllers (not shown), for example. Reference 1a designates the surface of the thermally tempered substrate 1 facing (closest or proximate to) the optical assembly 6 or the laser, respectively, and reference 1b designates the reverse surface of thermally tempered substrate 1 (the surface remote, or further away from, optical assembly 6 or the laser). The thickness of the thermally tempered substrate 1 (measured perpendicularly to the planes 1a and 1b, i.e., to the substrate plane) is labeled with d.

[0049] As FIG. 1A depicts, thermally tempered substrate 1 is aligned perpendicular 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 plane of the drawing). Viewed along the beam direction, the thermally tempered substrate 1 is positioned relative to the focal line 2b in such a way that the focal line 2b (viewed in the direction of the beam) starts before the surface 1a of the thermally tempered substrate 1 and stops before the surface 1b of the thermally tempered substrate 1, i.e. focal line 2b terminates within the thermally tempered substrate 1 and does not extend beyond surface 1b. In the overlapping area of the laser beam focal line 2b with thermally tempered substrate 1, i.e. in the portion of thermally tempered substrate 1 overlapped by focal line 2b, the extensive laser beam focal line 2b generates nonlinear absorption in thermally tempered substrate 1. (Assuming suitable laser intensity along the laser beam focal line 2b, which intensity is ensured by adequate focusing of laser beam 2 on a section of length 1 (i.e. a line focus of length 1), which defines an extensive section 2c (aligned along the longitudinal beam direction) along which an induced nonlinear absorption is generated in the thermally tempered substrate 1.) The induced nonlinear absorption results in formation of a damage track or crack in thermally tempered substrate 1 along section 2c. The damage track or crack formation is not only local, but rather may extend over the entire length of the extensive section 2c of the induced absorption. The length of section 2c (which corresponds to the length of the overlapping of laser beam focal line 2b with thermally tempered substrate 1) is labeled with reference L. The average diameter or extent of the section of the induced absorption 2c (or the sections in the material of thermally tempered substrate 1 undergoing the defect line or crack formation) is labeled with reference D. This average extent D may correspond to the average diameter 6 of the laser beam focal line 2b, that is, an average spot diameter in a range of between about 0.1  $\mu\text{m}$  and about 5  $\mu\text{m}$ .

[0050] As FIG. 1A shows, the thermally tempered substrate 1 (which is transparent to the wavelength  $\lambda$  of laser beam 2) is locally heated due to the induced absorption along the focal line 2b. The induced absorption arises from the nonlinear effects associated with the high intensity (energy density) of the laser beam within focal line 2b. FIG. 1B illustrates that the heated thermally tempered substrate 1 will eventually expand so that a corresponding induced tension leads to micro-crack formation, with the tension being the highest at surface 1a.

[0051] Representative optical assemblies 6, which can be applied to generate the focal line 2b, as well as a representative 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.

[0052] To insure high quality (regarding breaking strength, geometric precision, roughness and avoidance of re-machining requirements) of the surface of separation after cracking along the contour defined by the series of damage tracks, the individual focal lines used to form the damage tracks that define the contour of cracking should be generated using the optical assembly described below (hereinafter, the optical assembly is alternatively also referred to as

laser optics). The roughness of the separated surface is determined primarily by the spot size or the spot diameter of the focal line. A roughness of a surface can be characterized, for example, by an Ra surface roughness statistic (roughness arithmetic average of absolute values of the heights of the sampled surface). In order to achieve a small spot size of, for example, 0.5  $\mu\text{m}$  to 2  $\mu\text{m}$  in case of a given wavelength  $\lambda$  of laser 3 (interaction with the material of thermally tempered substrate 1), certain requirements must usually be imposed on the numerical aperture of laser assembly 6.

[0053] The laser cutting processes described herein generally generate a surface roughness of the exposed cut surface (edge) of a glass part of about 0.1-1.0  $\mu\text{m}$  Ra, where Ra is the statistical 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. More commonly, the Ra value for the cut edge is about 0.25-0.75  $\mu\text{m}$  for the laser processes described herein.

[0054] In order to achieve the required numerical aperture, the optics should, on the one hand, dispose of the required opening for a given focal length, according to the known Abbe formulae ( $\text{N.A.} = n \sin(\theta)$ , n: refractive index of the material to be processed,  $\theta$ : half the aperture angle; and  $\theta = \arctan(D/2f)$ ; D: aperture, f: focal length). On the other hand, the laser beam should illuminate the optics up to the required aperture, which is typically achieved by means of beam widening using widening telescopes between the laser and focusing optics.

[0055] 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 varies slightly.

[0056] FIG. 2A depicts one example method of generating a line focus. As stated above, there are many alternative methods of generating the line focus described herein, and embodiments are not limited to the example depicted in FIG. 2A. According to FIG. 2A (section perpendicular to the substrate plane at the level of the central beam in the laser beam bundle of laser radiation 2; here, too, laser beam 2 is perpendicularly incident to the thermally tempered substrate 1, i.e. incidence angle is  $0^\circ$  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 to 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 blocked by it. Only the beams in the outer perimeter range of beam bundle 2a (marginal rays, here labeled with 2aR) are not blocked 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, in this embodiment, is designed as a spherically cut, bi-convex lens 7.

[0057] Lens 7 is centered on the central beam and is designed as a non-corrected, bi-convex focusing lens in the form of a common, spherically cut lens. The spherical aberration of such a lens may be advantageous. 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 (defined by the distance required for the intensity of the beam to decrease to  $1/e^2$  of the peak 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. 2A 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**.

**[0058]** One potential disadvantage of this type of focal line is that the conditions (spot size, laser intensity) may vary along the focal line (and thus along the desired depth in the material) and therefore the desired type of interaction (no melting, induced absorption, thermal-plastic deformation up to crack formation) may possibly occur only in selected portions of the focal line. This means in turn that possibly only a part of the incident laser light is absorbed by the material to be processed in the desired way. In this way, the efficiency of the process (required average laser power for the desired separation speed) may be impaired, and the laser light may also be transmitted into undesired regions (parts or layers adherent to the substrate or the substrate holding fixture) and interact with them in an undesirable way (e.g. heating, diffusion, absorption, unwanted modification).

**[0059]** FIG. 2B-1-4 show (not only for the optical assembly in FIG. 2A, but also for any other applicable optical assembly **6**) that the position of laser beam focal line **2b** can be controlled by suitably positioning and/or aligning the optical assembly **6** relative to thermally tempered substrate **1** as well as by suitably selecting the parameters of the optical assembly **6**. As FIG. 2B-1 illustrates, the length **1** of the focal line **2b** can be adjusted in such a way that it exceeds the layer thickness **d** (here by factor **2**). If thermally tempered 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.

**[0060]** In the case shown in FIG. 2B-2, a focal line **2b** of length **1** is generated which corresponds more or less to the substrate thickness **d**. Since thermally tempered substrate **1** is positioned relative to line **2b** in such a way that line **2b** starts at a point outside the material to be processed, the length **L** of the section of extensive 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 **1** of focal line **2b**. FIG. 2B-3 shows the case in which the thermally tempered substrate **1** (viewed along the beam direction) is positioned above the starting point of focal line **2b** so that, as in FIG. 2B-2, the length **1** of line **2b** is greater than the length **L** of the section of induced absorption **2c** in thermally tempered substrate **1**. The focal line thus starts within the thermally tempered substrate **1** and extends beyond the reverse surface **1b**. FIG. 2B-4 shows the case in which the focal line length **1** is smaller than the substrate thickness **d** so that—in the 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 thermally tempered substrate **1** and ends near the surface **1b** within the thermally tempered substrate **1** (e.g.  $1=0.75 \cdot d$ ). The laser beam focal line **2b** can have a length **1** in a range of between about 0.1 mm and about 100 mm or in a range of between about 0.1 mm and about 10 mm, for example. Various embodiments can be configured to have length **1** of about 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm, 0.7 mm, 1 mm, 2 mm, 3 mm or 5 mm, for example.

**[0061]** It is particularly advantageous to position the focal line **2b** in such a way that at least one of surfaces **1a**, **1b** is covered by the focal line, so that the section of induced nonlinear absorption **2c** starts at least on one surface of the material to be processed. In this way, it is possible to achieve virtually ideal cuts while avoiding ablation, feathering and particulate generation at the surface.

**[0062]** FIG. 3 depicts another applicable optical assembly **6**. The basic construction follows the one described in FIG. 2A so that only the differences are described below. The depicted optical assembly is based 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 **1** is formed. For this purpose, aspheres can be used as optic elements of the optical assembly **6**. In FIG. 3, for example, a so-called conical prism, also often referred to as axicon, is used. An axicon is a 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 those of skill in the art; the cone angle in the example is  $10^\circ$ . The apex of the axicon labeled here with reference **9** is directed towards the incidence direction and centered on the beam center. Since the focal line **2b** produced by the axicon **9** starts within its interior, thermally tempered substrate **1** (here aligned perpendicularly to the main beam axis) can be positioned in the beam path directly behind axicon **9**. As FIG. 3 shows, it is also possible to shift thermally tempered substrate **1** along the beam direction due to the optical characteristics of the axicon while remaining within the range of focal line **2b**. The section of extensive induced absorption **2c** in the material of thermally tempered substrate **1** therefore extends over the entire depth **d**.

**[0063]** However, the depicted layout is subject to the following restrictions. Since the region of focal line **2b** formed by axicon **9** begins within the axicon **9**, a significant part of the laser energy is not focused into the section of induced absorption **2c** of focal line **2b**, which is located within the material, in the situation where there is a separation between axicon **9** and the material to be processed. Furthermore, length **1** of focal line **2b** is related to the beam diameter through the refractive indices and cone angles of axicon **9**. This is why, in the case of relatively thin materials (several millimeters), the total focal line is much longer than the thickness of the material to be processed, having the effect that much of the laser energy is not focused into the material.

**[0064]** For this reason, it may be desirable to use an optical assembly **6** that includes both an axicon and a focusing lens. FIG. 4A 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. 4A, this first optical

element is an axicon **10** with a cone angle of  $5^\circ$ , which is positioned perpendicularly to the beam direction and centered on laser beam. 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 the 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** is circularly incident on the outer radial portion 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 in this embodiment. The circular transformation of the laser beam by axicon **10** is labeled with the reference SR.

**[0065]** FIG. 4B depicts the formation of the focal line **2b** or the induced absorption **2c** in the material of thermally tempered substrate **1** according to FIG. 4A 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 length **1** of the focal line **2b** in beam direction is exactly identical with the thickness  $d$  of thermally tempered substrate **1**. Consequently, an exact positioning of thermally tempered substrate **1** along the beam direction should be provided to position the focal line **2b** exactly between the two surfaces **1a** and **1b** of thermally tempered substrate **1**, as shown in FIG. 4B.

**[0066]** 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 (annularly) over a particular outer radial region, which, on the one hand, serves to realize the required numerical aperture and thus the required spot size, and, on the other hand, however, the circle of diffusion diminishes in intensity after the 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 **1** 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.

**[0067]** If the crack formation is intended to continue to the back side of the layer or material to be processed, the circular (annular) illumination still has the advantage that: (1) the laser power is used optimally in the sense that most of the laser light remains concentrated in the required length of the focal line, and (2) it is possible to achieve a uniform spot size along the focal line—and thus a uniform separation process along the damage tracks produced by the focal lines—due to the circularly illuminated zone in conjunction with the desired aberration set by means of the other optical functions.

**[0068]** Instead of the plano-convex lens depicted in FIG. 4A, it is also possible to use a focusing meniscus lens or another higher corrected focusing lens (asphere, multi-lens system).

**[0069]** In order to generate very short focal lines **2b** using the combination of an axicon and a lens depicted in FIG. 4A, a very small beam diameter of the laser beam incident on the axicon may be needed. This has the practical disadvantage that the centering of the beam onto the apex of the axicon must be very precise and that the result is very sensitive to directional 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.

**[0070]** As shown in FIG. 5, both effects can be avoided by including another lens, a collimating lens **12** in the optical assembly **6**. The additional collimating 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  $f$ .

**[0071]** The optical assembly **6** depicted in FIG. 5 is thus based on the one depicted in FIG. 4A 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 focal line **2b** from the focusing lens **11** as  $z2$  (always viewed in beam direction). As shown in FIG. 5, the circular radiation SR formed by axicon **10**, which is incident 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 intended to be generated so that the circle width  $br$  of approximately 4 mm at collimating lens **12** is reduced to approximately 0.5 mm at lens **11** due to the focusing properties of collimating lens **12** (circle diameter  $dr$  is 22 mm in the example).

**[0072]** In the depicted example, it is possible to achieve a length of the focal line **1** 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, a collimating lens with a focal length  $f=150$  mm, and choosing distances  $Z1a=Z1b=140$  mm and  $Z2=15$  mm.

**[0073]** Laser processing methods for cutting thermally tempered substrates will now be described. Referring to FIG. 6A, a thermally tempered substrate **1**, such as a thermally tempered glass substrate, is schematically illustrated. The thermally tempered substrate **1** includes a first surface **1a** and a second surface **1b**. Extending from the first and second surfaces **1a**, **1b** toward an interior of the thermally tempered substrate **1** are compressive regions **1c** under compressive stress. An inner tension region **1d** under tension is disposed between the compressive regions **1c** and

balances the compressive stress of the compressive regions 1c. The depth of the compressive regions (i.e., depth of layer (“DOL”)) depends on the tempering process. As an example and not a limitation, for thermally tempered glass, the DOL may be greater than 100  $\mu\text{m}$ . FIG. 6B shows a typical stress profile of a thermally tempered glass substrate. The exact level of internal stress and specific functional dependence will depend on the exact thermally tempering conditions and the thickness of the glass substrate, but in general the functional dependence of the stress will take a parabolic shape, with the highest magnitude of compressive stress near the glass surfaces, and the highest magnitude of the tensile stress being near the center of the glass substrate. At a certain depth from each of the glass surfaces, the stress crosses over from being compressive to tensile, and these crossover points define the boundaries of the compressive and tensile regions show in FIG. 6A.

**[0074]** It is noted that other laser processes typically cut the substrate by introducing local damage either near the surface of the glass or at a specific location deep within the glass. Mechanical cutting processes cut by inducing a vent or crack at the topmost surface of the glass. In such cases, it may be challenging to make a damage zone that fully penetrates the thick compressive stress layer (greater than about 100  $\mu\text{m}$ ) that can be present in thermally tempered glass. This means it may be difficult to initiate a crack in a controlled manner in thermally tempered glass using either mechanical or past known laser methods. In contrast, the laser methods described herein are able to rapidly form damage tracks that can extend much further in the dimension perpendicular to the glass surface (multiple millimeters), and even can be made to extend all the way through the glass thickness. This allows greater control of the fracture plane orientation than is available with other laser methods.

**[0075]** To cut thermally tempered glass, the wavelength of the pulsed laser beam should be transparent to the material. As an example and not a limitation, the wavelength may be 1064 nm laser. The pulse duration and intensity should be short enough to achieve the multi-photon absorption effect described above. Ultra-short pulse lasers may be utilized, such as picosecond or femtosecond laser sources. In some embodiments, a  $\sim 10$  picosecond pulsed laser may be utilized. As an example and not a limitation, with a line focus of between about 1 mm and about 3 mm extent, and a  $\sim 10$  picosecond pulsed laser that produces output power of greater than about 50 W at a repetition rate of 200 kHz (250  $\mu\text{J}/\text{pulse}$ ), then the optical intensities in the line region can easily be high enough to create non-linear absorption in the thermally tempered glass substrate.

**[0076]** Note that the operation of such a picosecond laser described herein creates a “pulse burst” 5 sub-pulses 5a. FIG. 7A depicts two successive pulse bursts 5, each comprising three sub-pulses 5a, 5a', and 5a" (collectively “5a”). 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 sub-pulses. Each pulse burst contains multiple individual sub-pulses 5a (such as at least 2 sub-pulses, at least 3 sub-pulses, at least 4 sub-pulses, at least 5 sub-pulses, at least 10 sub-pulses, at least 15 sub-pulses, at least 20 sub-pulses, or more) of very short duration. That is, a pulse burst 5 is a “pocket” of sub-pulses 5a, and the pulse bursts 5 are separated from one another by a longer duration than the separation of individual adjacent pulses within each burst. Referring to FIG. 7B, which plots

laser emission against time for sub-pulse 5a of FIG. 7A, sub-pulses may have a 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). These individual sub-pulses (e.g., sub-pulses 5a, 5a', and 5a") within a single pulse burst 5 are referred to as sub-pulses herein to denote the fact that they occur within a single pulse burst. The energy or intensity of each individual sub-pulse 5a, 5a', 5a" within the pulse burst 5 may not be equal to that of other sub-pulses within the pulse burst, and the intensity distribution of the multiple sub-pulses within a pulse burst often follows an exponential decay in time governed by the laser design.

**[0077]** Referring to FIG. 7C, preferably, each sub-pulse (e.g., sub-pulses 5a, 5a', 5a") within the pulse burst 5 of the exemplary embodiments described herein are separated in time from the subsequent sub-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 each sub-pulses (sub-pulse-to-sub-pulse separation) within a pulse burst 5 is relatively uniform ( $\pm 10\%$ ). For example, in some embodiments, each sub-pulse within a pulse burst may be separated in time from the subsequent sub-pulse by approximately 20 nsec (50 MHz). For example, for a laser that produces a sub-pulse separation  $T_p$  of about 20 nsec, the sub-pulse-to-sub-pulse separation  $T_p$  within a pulse burst is maintained within about  $\pm 10\%$ , or is about  $\pm 2$  nsec. The time between each pulse burst 5 of sub-pulses 5a (i.e., time separation  $T_b$  between pulse bursts) will be much longer (e.g.,  $0.25 \mu\text{sec} \leq T_b \leq 1000 \mu\text{sec}$ , for example 1-10  $\mu\text{sec}$ , or 3-8  $\mu\text{sec}$ ). In some of the exemplary embodiments of the laser described herein, the time separation  $T_b$  is around 5  $\mu\text{sec}$  for a laser with burst repetition rate or frequency of about 200 kHz. The laser burst repetition rate (also referred to as burst repetition frequency herein) is defined as the time between the first sub-pulse 5a in a pulse burst 5 to the first sub-pulse 5a in the subsequent pulse burst 5. In some embodiments, the 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 sub-pulse in each pulse burst to the first pulse in the subsequent pulse burst may be 0.25  $\mu\text{sec}$  (4 MHz burst repetition rate) to 1000  $\mu\text{sec}$  (1 kHz burst repetition rate), for example 0.5  $\mu\text{sec}$  (2 MHz burst repetition rate) to 40  $\mu\text{sec}$  (25 kHz burst repetition rate), or 2  $\mu\text{sec}$  (500 kHz burst repetition rate) to 20  $\mu\text{sec}$  (50 kHz burst repetition rate). The exact timings, pulse durations, and burst repetition rates can vary depending on the laser design, but short sub-pulses ( $T_d < 20$  psec and preferably  $T_d \leq 15$  psec) of high intensity have been shown to work particularly well.

**[0078]** 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-pulse laser, the use of a pulse burst sequence that spreads the laser energy over a rapid sequence of sub-pulses within the burst 5 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 occurs 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.

**[0079]** In contrast, with a pulse burst laser, the intensity during each sub-pulse **5a** within the pulse burst **5** can remain very high—for example three 10 psec sub-pulses **5a** spaced apart in time by approximately 10 nsec still allows the intensity within each sub-pulse to be approximately only three times lower than that of a single 10 psec pulse, while the laser is able to interact with the material over a timescale that is now three orders of magnitude larger. This adjustment of multiple sub-pulses **5a** within a pulse 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, sub-pulse durations, and burst repetition rates can vary depending on the laser design, but short sub-pulses (<15 psec, or ≤10 psec) of high intensity have been shown to work well with this technique.

**[0080]** The defect line or a hole is formed in the material when a single pulse burst **5** of sub-pulses **5a** strikes essentially the same location on the glass substrate. That is, multiple sub-pulses **5a** within a single pulse burst **5** correspond to a single defect line or a hole location in the glass. Because the glass substrate is translated (for example by a constantly moving stage, or the beam is moved relative to the glass), the individual sub-pulses **5a** within the pulse burst **5** cannot be at exactly the same spatial location on the glass substrate. However, they are well within 1 μm of one another, i.e., they strike the glass substrate at essentially the same location. For example, the sub-pulses **5a** may strike the glass substrate at a spacing  $s_p$ , where  $0 < s_p \leq 1000$  nm from one another. For example, when a location of the glass substrate is hit with a pulse burst **5** of 20 sub-pulses, the individual sub-pulses **5a** within the pulse burst **5** strike the glass within 250 nm of each other. Thus, in some embodiments,  $1 \text{ nm} < s_p < 250 \text{ nm}$ . In some embodiments,  $1 \text{ nm} < s_p < 100 \text{ nm}$ .

**[0081]** As described above, the pulse burst produced by the pulsed laser is used to rapidly deposit energy along a defined line extending through the thermally tempered substrate, creating a damage track that typically extends approximately 1 mm to 3 mm through the bulk of the thermally tempered substrate. The length of the damage track depends on the focal length of the optics used.

**[0082]** Referring now to FIG. 8, a thermally tempered substrate **1** having a sequence of damage tracks **13** formed by a laser process is schematically illustrated. The damage tracks **13** generally take the form of holes with open interior dimensions (i.e., width  $w$ ) of about 0.1 μm to about 1.5 μm. The holes may or may not be continuous in opening throughout the length of the damage track, as they may be blocked or closed in regions. Additionally, the modified glass or cracked region around each damage track **13** can be signifi-

cantly larger, ranging from a few microns to many tens of microns, the extent of which can depend on the exact dimension of the line focus, the amount of burst energy used to form each damage track **13**, and the exact laser conditions such as the number of sub-pulses per pulse burst. Thus, it is possible to create a microscopic (i.e., <2 μm and >100 nm in diameter in some embodiments, and <0.5 μm and >100 nm in some embodiments) elongated “hole” (also referred to herein as a perforation or a defect line) in transparent material using a single high energy pulse burst. These individual perforations may be created at rates of several hundred kilohertz (several hundred thousand perforations per second, for example). Thus, with relative motion between the source and the material, these perforations or damage tracks **13** may be placed at any desired location within the substrate. In some embodiments, the damage track **13** is a “through hole,” which is a hole or an open channel that extends from the top to the bottom of the transparent material. In some embodiments, the damage track **13** may not be a continuous channel, and may be blocked or partially blocked by portions or sections of solid material (e.g., glass). As defined herein, the internal diameter of the damage track **13** is the internal diameter of the open channel or the air hole (or void). For example, in the embodiments described herein, the internal diameter of the damage track **13** is <500 nm, for example ≤400 nm, or ≤300 nm. The disrupted or modified area (e.g., compacted, melted, or otherwise changed) of the material surrounding the holes in the embodiments disclosed herein preferably has diameter of <50 μm (e.g., <10 μm).

**[0083]** In the illustrated example, the laser beam focal line **2b** created by the pulsed laser beam **2** is positioned within the thermally tempered substrate **1** extending from the first surface **1a**. The damage tracks **13** have a length  $L$  within the bulk of the thermally tempered substrate **1**. At least a portion of each damage track **13** is within the inner tension region **1d** of the thermally tempered substrate **1**. As stated above, each damage track **13** may be created by a burst of sub-pulses, or it may be fully formed by a single pulse. Additional pulses do not make the damage track **13** extend deeper through the material; however they may alter the exact dimensions of the damage track **13** or the extent of the modified material around it.

**[0084]** The lateral spacing (i.e., pitch  $p$ ) between each damage track is determined by the pulse rate of the laser as the thermally tempered substrate **1** is translated underneath the focused laser beam (or, alternatively, as the focused laser beam is translated with respect to the thermally tempered substrate). To produce damage tracks **13** at different pitches, the laser may be triggered to emit optical radiation at longer or shorter intervals. The selection of the pitch between damage tracks **13** may be governed by the hardness of the thermally tempered substrate **1** (i.e., its tendency to produce microcracks) and the stress level in the thermally tempered substrate **1** that helps the microcracks propagate. In general, thermally tempered substrates with higher levels of stress are cut with wider spacing between the damage tracks, and thermally tempered substrates with lower levels of stress are cut with damage tracks having closer spacing therebetween. As a non-limiting example, the lateral spacing may be between 2 μm and 20 μm.

**[0085]** Formation of each damage track **13** within the bulk of the thermally tempered substrate **1** causes one or more microcracks **14** to extend from the damage track **13** due at



least in part to the internal stresses of the thermally tempered substrate **1**. It should be understood that the microcracks **14** are shown schematically in FIG. **8**, and that they may take on shapes and/or directions other than those depicted in FIG. **8**. Further, in some cases, only one crack or microcrack may extend from a damage track **13**.

**[0086]** As shown in FIG. **8**, the microcracks extend between adjacent damage tracks **13**. Without being bound by theory, it is believed that the small lateral extent of the damage (i.e., the microcrack(s) **14** extending from a damage track **13** in a direction generally parallel with the first or second surface **1a**, **1b**), with the long depth dimension **L** of the damage track **13**, enable this laser method to cut thermally tempered glass substrates. By keeping the damage small laterally, the cracks or microcracks **14** do not grow too rapidly or become too large before the next damage track is made. Further, by making the damage track relatively long (i.e., longer than the microcracks **14**), the process assures that the inner tension region **1d** of the thermally tempered glass substrate **1**, which is buried very far from the first and second surfaces **1a**, **1b** in the case of thermally tempered glass, can be reached. If damage does not extend to the inner tension region **1d**, then cracks will not grow, or more importantly they will not grow in a time controlled manner.

**[0087]** FIG. **8** schematically depicts a thermally tempered substrate **1** having only been partially laser processed by the methods disclosed herein. Several damage tracks **13** have been created, with microcracks **14** extending therefrom. The illustrated focal line **2b** will form another damage track **13'** into the bulk of the thermally tempered substrate **1**. As the damage track **13'** is formed **13** (and/or just after it is formed), microcracks **14'** begin to propagate therefrom. The relative speed of the laser beam **2** with respect to the thermally tempered substrate **1** is such that the laser beam focal line **2b** is advanced with respect to the thermally tempered substrate **1** in the direction indicated by arrow **30** such that the microcracks **14'** will be guided toward the next, not-yet-formed damage track within the series of damage tracks. In this manner, the microcracks are guided along the damage line **15** formed by the damage tracks **13** and the thermally tempered substrate **1** is successfully cut along this damage line **15**.

**[0088]** Without being bound by theory, the methods described herein may be able to cut thermally tempered substrates because of the ability to quickly and clearly define a large damage plane or contour throughout most or all of the thickness of the body of the thermally tempered substrate before a strong enough internal damage event occurs that causes micro-cracks to propagate. This now-defined damage plane or contour then guides any subsequent cracking, allowing the material to separate along the pre-defined contour, rather than travelling in an uncontrolled manner which will cause the glass sheet to fragment into a multitude of pieces. Other methods (other laser and mechanical score methods) are not able to fully establish this damage plane or contour before the high internal stress in such a thermally tempered substrates is released in response to the damage the cutting processes introduces, meaning that the subsequent cracking is uncontrolled.

**[0089]** Use of a line focus to establish the internal damage allows one to define a very long region (e.g., about 1 mm or longer) with regard to the thickness of the thermally tempered substrate in a single pass, in contrast to conventional laser methods which only create damage over much shorter

regions. Additionally, the use of a line focus spreads the laser energy out over along a linear region with no particular location in that linear region having much higher (e.g. >2-3 $\times$ ) energy density than any other.

**[0090]** In contrast, focusing a Gaussian beam inside a substrate will create small regions of damage, often only tens of microns, or possibly a hundred microns, in extent. Thus, this does not define a full "wall" of damage in a thermally tempered substrate that is many millimeters thick unless many, many passes (many tens of passes) are performed. Further, by its very nature, a Gaussian beam focus is far more intense in a small local region along the optical axis (the focus) of beam propagation than a few Rayleigh ranges away from that focus point. Thus, if the Gaussian beam is made intense enough to define a damage track over tens of microns or more, at the focus spot itself it is quite easy to create damage strong enough that it will initiate the uncontrolled cracking in sheet. This makes any process window that allows definition of a damage plane without initiating uncontrolled cracking extremely narrow (or non-existent).

**[0091]** In the case of chemically strengthened glasses, a similar set of concepts applies. It is preferable to use a method such as a line focus to fully define a damage plane or contour within the glass substrate (ideally through the full depth of the glass substrate) before the micro-cracks propagate. However, such chemically strengthened glasses often do not have the same levels of internal forces present in them as thermally tempered glasses, so chemically tempered glasses may be more forgiving. If the damage plane is not fully formed, the subsequent cracking still may be controlled well enough to yield parts around the desired contours, and, in addition, upon initiation of damage to the tension layer such chemically strengthened sheets do not crack as quickly and have as rapid a crack propagation as the thermally tempered sheets. For lower central tension glasses (e.g. CT<20 MPa), the process windows are the widest and the most forgiving to not having fully formed damage planes or contours, whereas for higher central tension sheets (e.g. CT>20 MPa, especially CT>50 MPa), the process windows are narrower and require more rapid and complete formation of the pre-defined damage planes and contours. Finally, the thickness of chemically strengthened glass sheets is typically much less (generally <2.5 mm) than that of thermally tempered glass sheets (typically >3 mm). This means that defining a damage plane or contour throughout a substantial portion of the thickness of the glass sheet is more challenging for thermally tempered sheets, making use of a line focus of >1 mm in extent particularly advantageous as compared to using other laser methods.

**[0092]** The laser power and lens focal length (which determines the line focus length and hence power density) should be chosen to ensure full penetration of the glass and low micro-cracking. The laser power may be between about 25 W and about 60 W, for example. Attempts to cut the glass with higher power densities that could be induced by using too short a focal length lens (for example 30 mm or 40 mm) (which generates extremely high power densities in the lines focus), too high a burst energy or too dense a pitch between the damage tracks may result in fragmentation of the thermally tempered glass substrate. As a non-limiting example, for thermally tempered glass substrates, it has been found that a line focus length of about 1-3 mm, a laser burst energy of 150-750  $\mu$ J/burst, a damage track lateral spacing of 2-15

$\mu\text{m}$ , and a number of sub-pulses per burst of 2-15, are acceptable ranges. More preferably, burst pulse energies of 150-250p may be used, and sub-pulses/burst of 3-6 may be used, along with damage track lateral spacing of 5-10  $\mu\text{m}$ .

[0093] For thinner thermally tempered substrates (e.g., less than 2.5 mm) where the line focus passes completely through the bulk of the substrate, only a single pass of the pulsed laser beam may be needed. However, for thicker thermally tempered substrates, a multiple pass approach may be utilized, where the focus at each subsequent pass is raised to allow for complete cutting of the thermally tempered substrate after N passes. While it is possible to form damage tracks at a lower focus setting (i.e. further away from the focusing optics) than a set of previous formed damage tracks, it is generally preferred to make the lowest focus pass first, and then raise the focus on subsequent passes. This may help prevent previously formed damage tracks from interfering with the propagation of the laser beam.

[0094] FIG. 9 schematically depicts a thermally tempered substrate having three passes as depicted by laser pass lines A, B and C. For laser pass line A, the midpoint  $M_A$  of the laser beam focal line 2b is within a first compressive region 1c. For laser pass line B, the midpoint  $M_B$  of the laser beam focal line 2b is within the inner tension region 1d. For laser pass line C, the midpoint  $M_C$  of the laser beam focal line 2b is within a second compressive stress region 1c'.

[0095] FIGS. 10A and 10B are microscope images of a laser-cut edge 27 of a thermally tempered soda-lime glass sheet 20 using the laser processes described herein. Two laser passes were used to cut the thermally tempered glass sheet of thickness 3.2 mm. FIG. 10A depicts a first surface 21a of the thermally tempered glass sheet 20 (i.e., the laser-entrance surface). Although difficult to see in the microscope image, the entrances of individual damage tracks 23 may be seen along the first surface 21a of the thermally tempered glass sheet. The damage tracks 23 extend into the bulk of the thermally tempered glass sheet 20 through the compressive region 21c and into the inner tension region 21d. At a depth of approximately 592  $\mu\text{m}$ , a structural change 25 is seen in the laser-cut edge 27, which is likely correlated with the approximate depth of layer (depth of the inner tension region 21d) of this piece of thermally tempered glass.

[0096] FIG. 10B depicts a second surface 21b (i.e., the laser-exit surface). Although difficult to see in the microscope image, damage tracks 23 induced by the laser are present along the laser-cut edge 27 of the thermally tempered glass. Similar to FIG. 10A, a structural change 25' is present in the cut edge at a depth of approximately 546  $\mu\text{m}$ , which likely is correlated with the depth of layer of this piece of thermally tempered glass.

[0097] FIG. 11 shows a top view (a view from the top side of a piece of glass as opposed to a view from the cut edge side) of the cut edge 37 of a piece of thermally tempered glass 30. A periodic scalloping along the edge can be seen, with an approximate period of 6 microns. These features arise from the laser perforations or entrance holes that define the edge 37 along which the thermally tempered glass 30 has separated. The magnitude (depth perpendicular to the cut surface) of the scalloping is approximately 1 micron (e.g. <3 microns, or <2 microns, more frequently <1 micron).

[0098] FIGS. 12A, 12B, and 12C show side views (cross sections) of the exposed laser-cut edges 47A, 47B, 47C of

three pieces of approximately 3.2 mm thick thermally tempered glass sheets 40A, 40B, 40C where the glass sheets were cut without inducing catastrophic shattering (fragmentation). Between the three cases, the exact focus conditions were varied, leading to differing perforation (damage track) structures evident in the sides of each piece. In FIG. 12A, the damage tracks are seen in the upper 80% of the glass piece, but the bottom 20% exhibits only weak laser marks. In FIG. 12B, the damage tracks are present in the upper 90% of the glass piece, however there is a region approximately  $\frac{1}{3}$  of the distance from the top of the glass piece that is approximately 500 microns in depth that show where the fracture plane has not been precisely guided by the laser damage tracks. Nevertheless, the glass piece separated in a controlled manner as the majority of the depth of the glass piece had the fracture plane controlled. In FIG. 12C, the laser damage tracks are evident only in the center ~60% of the glass edge (which is a region more dominated by tensile stress), but are not present in the upper and lower ~20% of the edges, which are the regions more dominated by compressive stress. However, in all of the above cases (FIG. 12A, 12B, 12C), enough of a fraction of the depth of the glass was laser-perforated (>50% in all three cases) that the fracture plane was well controlled, and the glass pieces separated along the contours defined by the laser, as opposed to causing uncontrolled cracks propagation and catastrophic fragmentation of the glass sheets.

[0099] FIGS. 13A, 13B, and 13C show side views (cross sections) of the exposed laser-cut edges 57A, 57B, 57C of three pieces of approximately 5.5 mm thick thermally tempered glass sheets 50A, 50B, 50C where the glass sheets were cut without inducing catastrophic shattering (fragmentation). FIG. 13A shows the lower 80% of the depth of the glass sheet (about 4.5 mm) is covered by the laser damage tracks made by three laser passes. FIG. 13B has the upper 80% of the depth of the glass sheet covered by the damage tracks of three laser passes, and FIG. 13C has the middle of the glass sheet covered by the damage tracks, with the upper 5% not strongly perforated and the lower 15% not strongly perforated. The thin glass regions the extend horizontally across the images show the approximate regions where the laser damage tracks reach the end of their extent, showing that each pass is damaging or perforating a depth of approximately 1.5 mm. Note in all cases the >75% of the depth of the glass sheet is fully perforated, defining the glass fracture plane through the majority of the depth of the glass sheet. This allows all the 5.5 mm thermally tempered sheets to be successfully cut and separated without catastrophic fragmentation.

### Examples

[0100] Fully thermally tempered soda-lime glass having a compressive stress at the glass surface greater than 69 MPa (10,000 psi) of varying thicknesses were cut using the laser processing methods described herein. The following conditions were found to be efficient for cutting the material without fragmentation:

[0101] 1064 nm picosecond laser having an output power of greater than about 30 W

[0102] optical system parameters producing a line focus approximately 2 mm in length:

[0103] input beam diameter to axicon lens ~3 mm  $1/e^2$  diameter;

[0104] axicon angle=10 degrees;

- [0105] initial collimating lens focal length=125 mm; and
- [0106] final objective lens focal length=50 mm;
- [0107] 5 sub-pulses per pulse burst, (the laser burst energy delivered to the glass was approximately 160  $\mu$ J); and
- [0108] pitch between adjacent damage tracks of about 7  $\mu$ m, and the speed of the relative motion between the laser and the substrate of about 1 meter/sec. (The 7  $\mu$ m pitch and speed of 1 m/sec means that new damage tracks were being created at a rate of 142 kHz, or one every 7 microsecond).
- [0109] It should be understood that the above parameters are for illustrative purposes only, and that embodiments are not limited thereto. Other parameters are also possible, particularly for thermally tempered substrates other than fully thermally tempered soda-lime glass.

#### Example 1

[0110] For this Example, 3.2 mm thick fully thermally tempered soda lime glass sheets were cut using two laser passes at different focal heights within the glass sheet that created two damage lines of damage tracks. The laser and optical parameters were as provided above.

[0111] The focus of the first pass was set such that the line focus was centered at approximately the center of the glass sheet. The focus of the second pass was set with the optics physically 1.1 mm lower, which, accounting for the refractive index of the glass, would produce a line focus centered very close to the bottom of the glass. The glass did not separate until the second (lower) laser pass was completed. The focus settings that produced the best results are as follows:

[0112] first laser pass: focus set at  $z=2.3$  mm; and

[0113] second laser pass: focus set at  $z=1.18$  mm.

[0114] The fully thermally tempered glass sheet had enough stress (central tension) present within its bulk so that, after exposure with the above laser conditions, the glass substrate quickly separated along the path created by the damage line. As described above, it is important to keep the speed of the cut fast enough so that the microcracks emerging from the damage tracks do not “out run” the damage tracks. If the speed is set too low, the microcracks can become uncontrolled and do not follow the damage tracks, which leads to the glass eventually shattering.

#### Example 2

[0115] In the next Example, three laser passes were used to cut 5.5 mm thick thermally tempered soda lime glass sheets. The laser conditions were the same as provided in Example 1 except for the following:

[0116] first laser pass: focus set at  $z=2.8$  mm;

[0117] second laser pass: focus set at  $z=3.7$  mm;

[0118] third pass: focus is set at  $z=5.0$  mm; and

[0119] laser pulse energy: approximately 190  $\mu$ J.

[0120] The laser process made damage lines at progressively higher locations within the glass sheet. The first pass made a damage line in the lower third of the glass sheet, the second at about 0.9 mm physically higher than the first damage line with the optics (or, accounting for the refractive index, about 1.4 mm higher within the glass sheet), and the last pass about 1.3 mm higher with the optics (about 1.95

mm higher within the glass sheet). The glass sheet was cut after completion of the third pass.

[0121] The laser processing methods described herein may be used to not only cut thermally tempered substrates along straight lines, but also along curved lines to cut arbitrarily shaped articles from a thermally tempered substrate sheet.

[0122] It should now be understood that embodiments described herein provide for the laser cutting of thermally tempered substrates without the need for local de-tempering around a desired cut line. Embodiments use an ultra-short pulsed laser and a specialized optical delivery system to create precise damage tracks within the thermally tempered substrate. These damage tracks guide the propagation of microcracks caused by the internal stresses within the thermally tempered substrate, which allow crack propagation to be precisely controlled, thereby preventing the thermally tempered substrate from shattering during the cutting process. The methods described herein allow for glass to be cut to the desired shape after the tempering process. Additionally, embodiments described herein cut thermally tempered substrates at a high speed (e.g., about 1 m/second in some embodiments), and can form complex shapes such as rectangles, chamfers, radius corners, and circles. Further, the processes described herein may be used with a variety of substrate thicknesses and levels of tempering.

[0123] While exemplary embodiments have been described 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 encompassed by the appended claims.

What is claimed is:

1. A thermally tempered glass substrate comprising:

a first surface and a second surface, wherein the first surface and the second surface have a compressive stress greater than or equal to 24 MPa, and a stress profile within a body of the thermally tempered glass substrate between the first and second surface is parabolic;

an edge extending from the first surface to the second surface; and

a plurality of damage tracks positioned at the edge, wherein:

each individual damage track of the plurality of damage tracks has a diameter of less than or equal to 5  $\mu$ m and has a length of greater than or equal to 250  $\mu$ m;

adjacent damage tracks of the plurality of damage tracks are separated by a lateral spacing between about 2  $\mu$ m and about 20  $\mu$ m; and

the plurality of damage tracks extend 50% or more of a length of the edge.

2. The thermally tempered glass substrate of claim 1, wherein:

each individual damage track of the plurality of damage tracks has a length equal to or greater than 1 mm; and the plurality of damage tracks extend 75% or more of the length of the edge.

3. The thermally tempered glass substrate of claim 1, wherein each individual damage track of the plurality of damage tracks has an internal diameter of <500 nm.

4. The thermally tempered glass substrate of claim 1, wherein each of the plurality of damage tracks has an internal diameter of  $\leq 400$  nm.

5. The thermally tempered glass substrate of claim 1, wherein each of the plurality of damage tracks has an internal diameter of  $\leq 300$  nm.

6. The thermally tempered glass substrate of claim 1, wherein each individual damage track of the plurality of damage tracks has a length of about 1 mm to about 3 mm.

7. The thermally tempered glass substrate of claim 1, wherein adjacent damage tracks of the plurality of damage tracks are separated by a lateral spacing between about 2  $\mu\text{m}$  and about 15  $\mu\text{m}$ .

8. The thermally tempered glass substrate of claim 1, wherein each individual damage track of the plurality of damage tracks has a length of about 5  $\mu\text{m}$  to about 10  $\mu\text{m}$ .

9. A system for processing a thermally tempered substrate, the system comprising:

a laser source operable to emit a pulsed laser beam;  
a translation table operable to receive the thermally tempered substrate and to be translated along at least one axis;

an optical assembly disposed within an optical path of the pulsed laser beam that transforms the pulsed laser beam into a laser beam focal line, wherein at least a portion of the laser beam focal line is operable to be positioned within a bulk of the thermally tempered substrate such that the laser beam focal line generates an induced

multi-photon absorption within the thermally tempered substrate to produce a material modification within the thermally tempered substrate along the laser beam focal line; and

one or more controllers programmed to:

pulse the pulsed laser beam to form a sequence of pulse bursts comprising one or more sub-pulses; and

control the translation table to provide relative motion between the pulsed laser beam and the thermally tempered substrate along the at least one axis in a first laser beam pass such that the pulsed laser beam forms a sequence of damage tracks within the thermally tempered substrate, wherein individual damage tracks of the sequence of damage tracks are separated by a lateral spacing, and one or more microcracks extend between adjacent damage tracks of the sequence of damage tracks.

10. The system of claim 9, wherein:

the pulsed laser beam has laser power between about 25 W and about 60 W;

each pulse bursts of the sequence of pulse bursts have between 2 and 25 sub-pulses; and

the lateral spacing between damage tracks is between about 2  $\mu\text{m}$  and about 10  $\mu\text{m}$ .

\* \* \* \* \*