Title: GLASS CUTTING SYSTEMS AND METHODS USING NON-DIFFRACTING LASER BEAMS

Abstract: Embodiments are directed to systems for laser cutting at least one glass article comprising a pulsed laser assembly and a glass support assembly configured to support the glass article during laser cutting within the pulsed laser assembly, wherein the pulsed laser assembly comprise at least one non-diffracting beam (NDB) forming optical element configured to convert an input beam into a quasi-NDB beam; and at least one beam transforming element configured to convert the quasi-NDB beam into multiple quasi-NDB sub-beams spaced apart a distance of about 1 µm to about 500 µm; wherein the pulsed laser assembly is oriented to deliver one or more pulses of multiple quasi-NDB sub-beams onto a surface of the glass article, wherein each pulse of multiple quasi-NDB sub-beams is operable to cut a plurality of perforations in the glass article.
GLASS CUTTING SYSTEMS AND METHODS USING NON-DIFFRACTING LASER BEAMS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 62/087,406 filed on December 4, 2014 the content of which is relied upon and incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] Embodiments of the present disclosure are generally related to glass cutting systems and methods, and are specifically related to glass cutting systems and methods which utilize multiple non-diffracting sub-beams.

BACKGROUND

[0003] Focused short-pulsed laser beams are used for cutting and modifying transparent substrates, such as glass, through the process of nonlinear absorption via multi-photon ionization and subsequent ablation. Such laser systems must thus deliver a very small spot size and have high repetition rates in order to process materials at significant speeds. Typically laser processing has used Gaussian laser beams. The tight focus of a laser beam with a Gaussian intensity profile has a Rayleigh range \( Z_R \) given by:

\[
Z_R = \frac{\pi n_0 w_0^2}{\lambda_0}
\]  

[0004] The Rayleigh range represents the distance over which the spot size \( w_0 \) of the beam will increase by \( \sqrt{2} \) in a material of refractive index \( n_0 \) at wavelength \( \lambda_0 \). This limitation is imposed by diffraction. As shown in Eqn. 1 above, the Rayleigh range is related directly to the spot size, thus a tight focus (i.e. small spot size) cannot have a long Rayleigh range. Thus, the small spot size is maintained for an unsuitably short distance. 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.

[0005] Another approach to maintaining a tightly focused beam in a material is to use nonlinear filamentation via the Kerr effect, which yields a self-focusing phenomenon. In this process, the nonlinear Kerr effect causes the index at the center of the beam to increase, thereby creating a waveguide that counteracts the diffraction effect described above. The beam size can be maintained over a much longer length than that given in Eq. 1 above and is no longer susceptible to surface phase distortions because the focus is defined at the surface. To produce a sufficient Kerr effect, the power of the incident laser beam must exceed a critical value given by equation 2 below:

$$P_{cr} = \frac{3.72A}{0.345n_2} \quad (2)$$

where $n_2$ is the second-order nonlinear refractive index.

[0006] Despite the benefit of this extended focal range, generating beams in accordance with the Kerr effect undesirably requires much more power than the above described Gaussian beam approach.

[0007] Accordingly, there is a continual need for a beam generation method in a laser cutting system which achieves a beam(s) having a controlled spot size, longer focal length, while minimizing power requirements and increasing process speed.

SUMMARY

[0008] Embodiments of the present disclosure are directed to glass cutting systems and methods for cutting glass articles optical non-diffracting beams (NDB), specifically "complex" NDB beams having multiple-NDB sub-beams. This approach maintains the high intensities required to sustain the multi-photon absorption, and achieves beam propagation for a considerable distance before diffraction effects inevitably limit the beam focus. Additionally, the central lobe of the beam can be quite small in radius, and thus produce a high intensity beam with a controlled spot size. The approach of using
NDBs combines the benefits of the lower power associated with a Gaussian beam approach and the long focal range achieved by the filamentation process (Kerr effect).

Moreover, the present NDB embodiments may advantageously increase process speeds and lower operating costs, because it minimizes the number of pulses to cut through a substrate. The present optical system produces multiple simultaneous sub-beams from a single input beam pulse and thereby creates multiple damage spots or holes in a glass article from each pulse. A significant improvement in the cutting speed may be achieved when compared to a single beam method which delivers only one damage spot per pulse. (See FIG. 11 above)

According to one embodiment, a system for laser cutting at least one glass article is provided. The system comprises a pulsed laser assembly and a glass support assembly configured to support the glass article during laser cutting within the pulsed laser assembly. The pulsed laser assembly comprises at least one quasi-NDB beam forming optical element configured to convert an input beam into a quasi-NDB beam, and at least one beam transforming element configured to convert the quasi-NDB beam into multiple quasi-NDB sub-beams spaced apart a distance of about 1 µm to about 500 µm. The pulsed laser assembly is oriented to deliver one or more pulses of multiple quasi-NDB sub-beams onto a surface of the glass article, wherein each pulse of multiple quasi-NDB sub-beams is operable to cut a plurality of perforations in the glass article.

According to another embodiment, a method of laser cutting a glass article is provided. The method comprises feeding at least one glass article to a pulsed laser system that produces multiple quasi-non-diffracting beams (NDB) spaced apart a distance of about 1 µm to about 500 µm for every pulse, laser cutting the at least one glass article using the multiple quasi-NDB beams to achieve a plurality of perforations in the glass article, and separating the glass article along the perforations to yield a laser cut glass article.

According to yet another embodiment, another system for laser cutting at least one glass article is provided. The system comprises a pulsed laser assembly and a
glass support assembly configured to support the glass article during laser cutting within
the pulsed laser assembly. The pulsed laser assembly comprises at least one axicon
configured to convert an input beam (e.g., a Gaussian beam) into a Bessel beam, first
and second collimating lenses disposed downstream of the axicon, and at least one
beam transforming element oriented between the first and second collimating lenses.
The at least one beam transforming element is configured to convert the Bessel beam
into multiple sub-Bessel beams which are parallel and spaced apart a distance of about
1 µm to about 500 µm. The pulsed laser assembly is oriented to deliver one or more
pulses of multiple sub-Bessel beams onto a surface of the glass article, wherein each
pulse of multiple sub-Bessel beams is operable to cut a plurality of perforations in the
glass article. In one or more embodiments, the beam transforming element may be
disposed proximate a Fourier-transform plane generated by the first collimating lens or
oriented within a focal length of the second collimating lens.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0013] The following detailed description of specific embodiments of the present
disclosure can be best understood when read in conjunction with the drawings enclosed
herewith.

[0014] FIG. 1 is a schematic view of a Gaussian beam passing through the axicon to
produce a quasi-NDB Bessel beam.

[0015] FIG. 2A is a schematic view of a glass cutting system in accordance with one
or more embodiments of the present disclosure.

[0016] FIG. 2B is a close-up view of FIG. 2A depicting the laser cutting of the glass
article in accordance with one or more embodiments of the present disclosure.

[0017] FIG. 3A is a graphical illustration of a computer simulation, the graphical
illustration depicting a single-axis scan across the center of two Bessel sub-beams
separated by 5.84 µm.
FIG. 3B is a graphical illustration of a computer simulation, the graphical illustration depicting a two-dimensional cross-section of the two Bessel sub-beams of FIG. 3A.

FIG. 4A is a graphical illustration of a computer simulation, the graphical illustration depicting a single-axis scan across the center of two Bessel sub-beams separated by 3.23 μιτι, wherein a π phase shift is added to one beam.

FIG. 4B is a graphical illustration of a computer simulation, the graphical illustration depicting a two-dimensional cross-section of the two Bessel sub-beams of FIG. 4A.

FIG. 5A is a graphical illustration of a computer simulation, the graphical illustration depicting a single-axis scan across the center of three Bessel sub-beams separated by 5.85 μιτι.

FIG. 5B is a graphical illustration of a computer simulation, the graphical illustration depicting a two-dimensional cross-section of the three Bessel sub-beams of FIG. 5A.

FIG. 6A is a graphical illustration of a computer simulation, the graphical illustration depicting a single-axis scan across the center of three Bessel sub-beams separated by 3.23 μιτι, wherein a π phase shift is added to one beam.

FIG. 6B is a graphical illustration of a computer simulation, the graphical illustration depicting a two-dimensional cross-section of the three Bessel sub-beams of FIG. 6A.

FIG. 7 is a schematic depiction of an optical assembly used in the pulsed laser assembly wherein the beam transforming element is oriented proximate the Fourier-transform plane of an upstream collimating lens according to one or more embodiments of the present disclosure.

FIG. 8 is a schematic depiction of an optical assembly used in the pulsed laser assembly wherein the beam transforming element is oriented within a focal length of a
downstream collimating lens according to one or more embodiments of the present disclosure.

[0027] FIG. 9 is a schematic depiction of an alternative optical assembly with smaller optical elements according to one or more embodiments of the present disclosure.

[0028] FIG. 10 is a schematic depiction of yet another optical assembly with a reflective optical element according to one or more embodiments of the present disclosure.

[0029] FIG. 11 is a schematic depiction comparing damage spots produced by one, two, and three beam systems.

[0030] The embodiments set forth in the drawings are illustrative in nature and not intended to be limiting of the invention defined by the claims. Moreover, individual features of the drawings will be more fully apparent and understood in view of the detailed description.

DETAILED DESCRIPTION

[0031] Referring to the embodiments of the FIGS. 2A and 2B, a system 1 for laser cutting at least one glass article is shown. The system 1 comprises a pulsed laser assembly 10 and a glass support assembly 50 which supports the glass article 5 during laser cutting by the pulsed laser assembly 10. As shown in FIGS. 2A and 2B, the pulsed laser assembly 10 delivers one or more pulses of multiple quasi-NDB sub-beams 18A, 18B onto a surface of the glass article 5. Referring to FIG. 2B, the pulse (or complex beam) 18 of multiple quasi-NDB sub-beams 18A, 18B may cut a plurality of perforations 6A, 6B or in the glass article 5. As shown in the embodiment of FIG. 2A, the glass support assembly 50 is merely depicted as a conveyor; however, various other components such as a spindle chuck, robotic arm, etc are contemplated as suitable herein. These contemplated embodiments may cause the pulsed laser assembly 10 and the glass support assembly 50 to be moveable relative to one another during the laser cutting process.
Referring to FIG. 7, the pulsed laser assembly 10 comprises at least one NDB forming optical element 20 that converts an input beam 7 (e.g., a Gaussian beam) into a quasi-NDB beam 12 (See also FIG. 1), and at least one beam transforming element 40 which converts the quasi-NDB beam 12 into multiple quasi-NDB sub-beams 18A, 18B, 18C spaced apart a distance of about 1 \( \mu \text{m} \) to about 500 \( \mu \text{m} \).

As used herein, "quasi-NDB beam" means a created non-diffracting beam, typically a nondiffracting beam created from the conversion of an input beam (e.g., a Gaussian beam) to a non-diffracting beam. The quasi-NDB beam could encompass many beam types. As used herein, "input beam" may include any beam having a substantially uniform optical phase. In one embodiment, the input beam is a Gaussian beam. For example, the quasi-NDB may include a Bessel beam, an Airy beam, a Weber beam, or a Mathieu beam. In the embodiments described below, the quasi-NDB beam is a Bessel beam. The conversion of a Gaussian beam 7 by an axicon NDB forming optical element 20 to a Bessel quasi-NDB beam 12 is shown in FIG. 1. FIG. 1 depicts a single pulse Gaussian beam; however, the Gaussian beam source may also deliver the Gaussian beam in multiple pulses. In addition to axicons, various other NDB forming optical elements are contemplated, for example, a spatial light modulator, an elliptical lens, or combinations thereof. Bessel beams may be readily produced by axicons; however, other quasi-NDB beams are produced with other NDB forming elements 20.

Further as used herein, "multiple quasi-NDB sub-beams" does not mean separate NDB laser beams. "Multiple quasi-NDB sub-beams" means a complex beam having a plurality of spots. Referring to FIG. 3A, the two peaks 18A and 18B are two quasi-NDB sub-beams in the complex Bessel beam depicted therein. As shown in FIG. 1, Bessel beams tend to have a central peak at zero, which would constitute its beam spot. However, in accordance with the present embodiments, the Bessel beam is converted in the beam transforming element 40, such that the Bessel beam with a single spot is transformed into a modified Bessel beam having two spots corresponding to peaks 18A and 18B. These two spots or two quasi-NDB sub-beams are depicted in cross-section in FIG. 3B. FIGS. 4A and 4B depict another embodiment having 2 quasi-NDB sub-beams, and FIGS. 5A-6B depict embodiments with 3 quasi-NDB sub-beams.
18A, 18B, and 18C. While not shown, "multiple quasi-NDB sub-beams" encompasses complex beams having more than 2 or 3 quasi-NDB sub-beams.

[0035] Referring to FIGS. 7 and 8, the beam transforming element 40 converts a quasi-NDB beam 12 into multiple quasi-NDB sub-beams 18A, 18B, and 18C. The beam transformation essentially re-shapes the high intensity single quasi-NDB beam into multiple lower intensity sub-beams, which in most embodiments are spaced apart from one another. As shown in FIGS. 3A-6B, the multiple quasi-NDB sub-beams are depicted as being in parallel; however, it is contemplated that the multiple quasi-NDB sub-beams 18 could be angled such that they overlap with one another. In addition to generating the multiple quasi-NDB sub-beams, the beam transforming element 40 may optimize the spacing between the beams, and optionally may shift the phase of one or more of the multiple quasi-NDB sub-beams. By phase shifting the phase of at least one of the multiple quasi-NDB sub-beams, the intensity of the multiple quasi-NDB sub-beams may be added coherently. Depending on the glass cutting application, various spacings between sub-beams may be sought. For example, the spacing may be from about 1 μm to about 500 μm, or about 1 μm to about 200 μm, or about 1 μm to about 100 μm, or about 1 μm to about 50 μm, or about 1 μm to about 20 μm, or about 1 μm to about 10 μm, or about 1 μm to about 5 μm. Similarly, the degree of phase shift may vary with phase shifts ranging from about π/4 to about 2π, or about π/2 to about π being contemplated.

[0036] The beam transforming element 40 may comprise various components. For example and not by way of limitation, the beam transforming elements may comprise is a phase grating or phase plate, an amplitude grating, or combinations thereof. In specific embodiment, it may be beneficial to include a beam transforming element 40 which is a combination of a phase element and an amplitude element. These gratings may be square wave or sinusoidal; however, other complex shapes are contemplated herein. A further discussion of beam transforming elements 40 is provided below.

[0037] An amplitude-only grating may be defined by the following equation:
\( P_{\text{tot}}(u, v) = 0.5 + 0.5 \times \cos \left( \frac{2 \pi u}{T} \right) \)  (3)

[0038] Physically, this would be a much easier grating to make, because no phase shift is required; however, such a grating may produce many order beams, for example, a zeroth-order beam and two first-order beams. Thus, in some embodiments, a phase shift may be utilized to substantially limit the beams to a single order.

[0039] Phase-only gratings may be formed from a thickness or index grating in glass or using a programmable spatial light modulator. A square phase-only grating can more efficiently couple light into the sub-beams. For two beams, the most efficient phase-only grating may be defined by:

\[ P_{\text{tot}}(u, v) = e^{i \phi \sqrt{\text{rect}} \left( \frac{2 \pi u}{T} \right)} \]  (4)

Where \( \phi_0 = 1 \) and \( \sqrt{\text{rect}} \left( \frac{2 \pi u}{T} \right) \) is a square-wave function of \( u \) oscillating between -1 and +1 with a period of \( T \). With the square grating, additional diffraction orders may be present, but with the correct choice of phase amplitude they can be minimized. With the sinusoidal amplitude grating, there are only the two first-order beams.

[0040] To generate a third beam, it is possible to use \( \phi_0 = \arctan \left( \frac{\pi}{2} \right) \sim 1 \) rad to give:

\[ P_{\text{tot}}(u, v) = e^{i \sqrt{\text{rect}}(\cdots)} \]  (5)

which results in three beams.

[0041] In one or more embodiments, static phase elements can be made to various scales. However, it may be desirable to use programmable phase elements such as acousto-optic modulators (AOM), electro-optic modulators (EOM), spatial light modulators (SLM) and digital micro-mirror arrays (DMA).

[0042] Without being bound by theory, sub-beam spacings that preserve the characteristics of the input beam 7 are beneficial. As an example, a discussion
regarding combining two zeroth-order Bessel beams is provided below. This approach can be used for finding the optimal spacings for other quasi-NBD sub-beams.

[0043] As shown in FIG. 1, the Bessel function $J_0(x)$ is an oscillatory function (positive and negative) about zero. If two Bessel functions are added coherently with a lateral offset, they will interfere destructively when a positive peak in one function overlaps with a negative peak in the second function. Similarly, the beams will add constructively when two positive peaks add. The locations of the positive maxima and negative minima of the function $J_0(x)$ are given by the zeros of the higher-order Bessel function $J^N_0(x)$ (through a well-known relationship that $dJ_0(x)/dx=-J_1(x)$). These zeros are well known and the first few are given in Table 1 below. For roots beyond those shown in Table 1, the roots become equally spaced by $\approx \tau$, so simply add multiples of $\pi = 3.14159$ to the $7^{th}$ root.

[0044] The equation for optimal $\Delta x_{opt}$ that optimizes the peak intensity of the sub-beams may be defined as:

$$\Delta x_{opt,j} = \frac{\beta_j}{k_r}$$

(6)

where:

$$k_r = k - NA = \frac{2\pi n_o}{\lambda_o} - NA = \frac{2\pi n_o}{\lambda_o} \cdot \sin(\beta)$$

(7)

[0045] For $\lambda_o = 1.06 \mu m$ in air with numerical aperture ($NA$)=0.2 (or $\beta = 1.5^\circ$), we find $k_r = 1.855 \mu m^{-1}$ and the resulting optimal spacing is given in the $4^{th}$ column of Table 1 while column 5 gives the spacing for $NA=0.1$ (narrow cone angle of $\beta=5.7^\circ$). When the beams are added with no phase shift between them, we use the odd roots $j=3, 5, \text{etc.}$

[0046] An alternative approach for generating two beams would be to add the two coherent beams with a phase shift between them. If we add a $\pi$ shift to the relative optical phase, this is equivalent to multiplying one of the beams by a minus sign. Thus the positive peaks of one beam will add coherently to the negative peaks of the second
beam. This allows for efficient beam separations at the spacings labeled "N" in the third column of Table 1, corresponding to the even roots j=2, 4, etc.

`[0047] Table 1`

<table>
<thead>
<tr>
<th>j&lt;sup&gt;th&lt;/sup&gt; Root</th>
<th>J1 zero, β&lt;sub&gt;j&lt;/sub&gt;</th>
<th>Peak sign</th>
<th>Example Δx&lt;sub&gt;opt&lt;/sub&gt; (µm) NA = 0.2 k&lt;sub&gt;r&lt;/sub&gt;=1.1855 µm&lt;sup&gt;-1&lt;/sup&gt;</th>
<th>Example Δx&lt;sub&gt;opt&lt;/sub&gt; (µm) NA = 0.1 k&lt;sub&gt;r&lt;/sub&gt;=0.5928 µm&lt;sup&gt;-1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>P</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>3.8317</td>
<td>N</td>
<td>3.23</td>
<td>6.46</td>
</tr>
<tr>
<td>3</td>
<td>7.0156</td>
<td>P</td>
<td>5.92</td>
<td>11.84</td>
</tr>
<tr>
<td>4</td>
<td>10.1735</td>
<td>N</td>
<td>8.58</td>
<td>17.16</td>
</tr>
<tr>
<td>5</td>
<td>13.3237</td>
<td>P</td>
<td>11.24</td>
<td>22.48</td>
</tr>
<tr>
<td>6</td>
<td>16.4706</td>
<td>N</td>
<td>13.89</td>
<td>27.79</td>
</tr>
<tr>
<td>7</td>
<td>19.6159</td>
<td>P</td>
<td>16.55</td>
<td>33.09</td>
</tr>
</tbody>
</table>

`[0048] For illustration, FIG. 3A depicts a two spaced quasi-NDB sub-beams, and FIG. 4A shows the two spaced quasi-NDB sub-beams but with a π phase shifted added to one of the beams. Both FIGS 3A and 4A show optimal separations for which the sub-beam intensity is locally maximized. The out-of-phase beams in FIG. 4A can be placed very close together (~3 microns). This is important in the cutting of transparent substrates for creating nearly continuous damage zones. Similarly, FIG. 5A depicts three spaced quasi-NDB sub-beams 18A, 18B, and 18C, and FIG. 6A shows three spaced quasi-NDB sub-beams but with a π phase shifted added to the central beam 18B.

`[0049] For non-optimal spacing, the peak intensity is not maximized, but such spacings may still produce acceptable cutting behavior as long as sufficient laser power is available to achieve nonlinear material damage.

`[0050] Referring to the embodiments of FIG. 7-10, specific optical assembly 11 arrangements for the pulsed laser assembly 10 are depicted therein. As shown in FIGS. 7 and 8, the optical assembly 11 may comprise at least one collimating lens 31`
configured to narrow the quasi-NDB beam 12 from the at least one NDB forming optical element 20.

[0051] Further as shown in FIG. 7, the beam transforming element 40 may be oriented downstream of the collimating lens 3. In a further embodiment, the beam transforming element 40 may be oriented proximate a Fourier-transform plane 41 produced by the collimating lens 3. It is also contemplated to place the beam transforming element 40 at a location not proximate or within the Fourier-transform plane 41. Moreover as shown in FIG. 7, the optical assembly 11 may further comprise at least one additional collimating lens 32 downstream of the beam transforming element 40 which focus the multiple quasi-NDB sub-beams 18A, 18B, and 18C.

[0052] Referring again to the embodiment of FIG. 7, when the beam transforming element 40 is oriented behind the Fourier-transform plane 41 of collimating lens 3, the field A(u,v) at Fourier-transform plane 41 is multiplied by a transfer function P(u,v) to produce a new field A'(u,v) with two new angular components which are then imaged by collimating lens 32 to an image plane 17 to produce three quasi NDB sub-beams 18A, 18B, and 18C. The rays after beam transforming element 40 are depicted with dashed lines to indicate that the optical field in this region is a function beam transforming element 40.

[0053] As shown in the embodiment of FIG. 7, the focus 8 of the input beam 7 is placed in front of the first collimating lens 3 at a distance f₁, where f₁ is the focal length of the first collimating lens 3. A second lens 32 with a second focal length f₂ is placed a distance of f₁ + f₂ behind the first lens 3. The Fourier-transform plane 41 at a distance of f₁ behind the first lens 3 is the Fourier-transform plane of the first lens 3 and the optical field at this plane is known to be the optical Fourier transform A(u,v) of the input field a(x,y) at a distance f₁ in front of collimated lens 3:

\[
A(u, v) = \iint_{-\infty}^{\infty} a(x,y) e^{-\frac{2\pi i}{\lambda f_1} (xu+yv)} \, dx \, dy
\]  

(8)
The purpose of the second lens is to take the inverse Fourier transform of the optical field $A(u,v)$ in Fourier-transform plane $41$ and form an image $b(x,y)$ of the input beam in image plane $17$. It can be shown that:

$$
b(x',y') = \iint_{-\infty}^{\infty} A(u,v) \frac{2\pi ni}{\lambda f_2} e^{\frac{2\pi i}{\lambda f_2} (ux + vy)} dudv$$

(9a)

$$\frac{1}{f_2} a \left( \left( -\frac{f_1}{f_2} x', -\frac{f_1}{f_2} y' \right) \right)$$

(9b)

$$= M_0 (-Af, -My')$$

(9c)

If $f_1 \neq f_2$, the image will have a magnification $M \neq 1$ and the quasi NDB sub-beams may not be parallel. If $f_1 = f_2$, the image will have a magnification $M = 1$ and the quasi NDB sub-beams will be parallel.

Introducing the beam transforming element $40$ in the Fourier-transform plane $41$ has the effect of multiplying the Fourier-transform of the input field by the transfer function of this element:

$$bW = \iint_{-\infty}^{\infty} A(u,v) \frac{2\pi ni}{\lambda f_2} e^{\frac{2\pi i}{\lambda f_2} (ux + vy)} dudv$$

(10a)

$$= \iint_{-\infty}^{\infty} A(u,v)P(u,v) \frac{2\pi ni}{\lambda f_2} e^{\frac{2\pi i}{\lambda f_2} (ux + vy)} dudv$$

(10b)

It is known that certain optical elements can shift an input beam in an arbitrary direction, can impart a tilt to the focal region, and can scale the amplitude of the output beam. Other elements and apertures can be used to filter unwanted spatial frequencies from the beam in order to mitigate or create impairments to the optical beam. In this disclosure, we will focus on the lateral shifting of quasi-NDB sub-beams to generate multiple quasi NDB sub-beams.

The phase transformation to accomplish a lateral shift $(\Delta \chi, \Delta y)$ is:

$$P(u, v) = e^{\frac{2\pi i}{\lambda f_2} (u \Delta x + v \Delta y)}$$

(11)
From above it can be seen that:

\[ b'(x', y') = \frac{Cr}{\infty} A(u,v) P(u,v) \int e^{-i2\pi(ux + vy)} du \]

\[ = \int e^{\frac{2\pi ni}{f_2} (uAx + vAy)} e^{-\frac{2\pi ni}{f_2} (ux' + vy')} du \]

\[ = M(\alpha (x' - \Delta x), -M(y' - Ay)) \]

Thus, the output field \( b'(x', y') \) in image plane 17 is a scaled and shifted version of the input field \( a(x,y) \).

It is also known that multiple quasi-NDB sub beams can be produced by summing different phase shifts:

\[ \sum_{j=1}^{N} c_j e^{\frac{2\pi ni}{f_2} (uAx_j + vAy_j)} \]

For the special case of two equal beams, \( N=2 \) spaced by \( x_0 \):

\[ P_{tot}(u,v) = \frac{1}{2} \left[ e^{\frac{2\pi ni}{f_2} (u\Delta x_0)} + e^{\frac{2\pi ni}{f_2} (u\Delta y_0)} \right] \]

\[ = \cos \left( \frac{2\pi n u}{f_2} \right) \]

\[ = \cos \left( \frac{2\pi n u}{f_2} \right) T \]

where \( T = \frac{2\lambda f_2}{n\Delta x_0} \). In this instance, \( P_{tot}(u,v) \) is simply a cosinusoidal amplitude diffraction grating of period \( T \). When a phase shift is introduced between the two beams we find:

\[ P_{tot}(u,v) = \frac{1}{2} e^{i\phi} e^{\frac{2\pi ni}{f_2} (\Delta x_n)} + e^{-\frac{2\pi ni}{f_2} (\Delta y_n)} \]

\[ = \cos \left( \frac{2\pi n u}{f_2} + \frac{\phi}{2} \right) \]
[0062] So that a phase shift of $\phi = \pi$ between the sub-beams adds a phase of $\phi/2$ to the cosine which makes it a sine function. Practically, this corresponds to a lateral shift of the grating by a quarter of a period or 7/4.

[0063] In addition to the arrangement of FIG. 7, the NBD forming optical element 20 (e.g., axicon) may be at a distance greater or less than the focal length $f_1$ of lens 31. This may lead to an uncollimated region between the collimating lenses 31 and 32, and thus may impact the choice of the beam transforming element 40. Additionally, various distances are contemplated between collimating lenses 31 and 32. For example, the distance between collimating lenses 31 and 32 differ may be greater or less than $f_1 + f_2$.

[0064] Alternatively, the embodiments above describe the positioning of the beam transforming element 40 after lens 31; however, various other positions are also contemplated. For example, and not by way of limitation, the beam transforming element 40 may be positioned before collimating lens 31 or after collimating lens 32.

[0065] Various additional optical assemblies are also contemplated herein. In the embodiment of FIG. 8, the optical assembly may also include the beam transforming element 40 within the focal length ($f_2$) of collimating lens 32, which is downstream of the beam transforming element 40. As shown, this may be achieved by placing the beam transforming element 40 in close proximity to collimating lens 31, which is upstream of the beam transforming element 40.

[0066] In an additional embodiment depicted in FIG. 9, the optical assembly 11 may comprise comprising multiple collimated regions 30 and 35. In the embodiment of FIG. 9, the multiple collimated regions 30 and 35 include a large collimated region 30 and a small collimated region 35 downstream of the large collimated region 30. The large collimated region 30 may include one or multiple collimating lenses 31 and 32 that narrow the NDB beam from the at least one NDB forming optical element 20. Moreover, the optical assembly 11 may include a small collimated region 35 downstream of the large collimated region 30 which narrows the quasi-NDB beam from the prior to splitting in the beam transforming element 40. The small collimated region 35 includes one or a plurality of collimating lenses 36 and 37. While the beam transforming element 40 is
disposed in the small collimated region 35 in the embodiment of FIG. 9, it is contemplated that the beam transforming element 40 may be disposed in the large collimated region 30.

[0067] Without being bound by theory, having two collimating regions 30 and 35 as shown in FIG. 9 is useful to accommodate a Bessel beam Rayleigh range optimized for large diameter beams with large numerical apertures. For example, the diameter of the beam between collimating lens 31 and collimating lens 32 is large e.g., 10-30 mm. Thus, to provide small focal spots, it may be necessary to include the small collimated region 35 that is small in diameter.

[0068] Referring to FIG. 10, an alternative optical assembly may include a reflective beam transforming element 40. In this instance, after the input beam 7 is converted by an axicon 20 into a quasi-NDB beam 12, it is linearly polarized and passes through a polarizing beam splitter 48 in the collimating region between collimating lenses 31 and 32. The quasi-NDB beam 12 then passes through a quarter wave plate 46 to become circularly polarized before being recollimated with demagnification by collimating lenses 32 and 33. The quasi-NDB beam 12 is converted into multiple quasi-NDB-beams, which are then retroreflected off the reflective beam transforming element 40 and back through collimating lenses 33 and 32. The multiple quasi-NDB-beams are further rotated in polarization by the quarter wave plate 46 and thereby achieve the opposite linear polarization to input beam 7. This new polarization is reflected by beam splitter 48 and the beam is focused to its final size by collimating lens 38.

[0069] As stated above, it is also anticipated that the optical assemblies may have apertures to block unwanted light from reaching the image plane 17. This may be the case with phase only gratings that have higher-order diffraction patterns. The magnification of the final image is dependent on the choice of focal lengths. Without being bound by theory, the target beam spacing is specified in the image plane and can thus be tuned by both the grating and the optical magnification.
Turning now to glass cutting applications, the present embodiments may yield improved formation of single lines of damage (i.e., perforations) and improved formation of multiple lines to form arrays of damage sites.

In the case of the single damage line, the multiple sub-beams are aligned with the scan direction of the laser. For example, if a 100 kHz laser system is used to create damage sites spaced at 3 microns, a single beam optical system could be scanned 3 microns every 10 microseconds for a cutting speed of 0.5 m/s. However, with 3 sub-beams, the same system could run at 1.5 m/s by moving the compound beam spot by 9 microns in the same 10-microsecond time interval.

In the case of the multiple damage lines for array applications as depicted in FIG. 11, the multiple sub-beams are aligned orthogonally to the scan direction of the laser. For example as depicted in FIG. 11, if a 100 kHz laser system is used to create a 10,000x1 0,000 damage sites spaced at 10 microns, a single beam optical system would require 1000 seconds to create the array. A three sub-beam system could finish the same task in 334 seconds.

As would be familiar to one of skill in the art, various other components are contemplated for the laser cutting assembly. For example, the laser cutting assembly may include some mechanism for separating the glass article along the perforations to yield a laser cut glass article. This may include thermal shock devices, cracking beams, etc.

It is further noted that terms like "preferably," "generally," "commonly," and "typically" are not utilized herein to limit the scope of the claimed invention or to imply that certain features are critical, essential, or even important to the structure or function of the claimed invention. Rather, these terms are merely intended to highlight alternative or additional features that may or may not be utilized in a particular embodiment of the present disclosure.

It will be apparent that modifications and variations are possible without departing from the scope of the disclosure defined in the appended claims. More
specifically, although some aspects of the present disclosure are identified herein as preferred or particularly advantageous, it is contemplated that the present disclosure is not necessarily limited to these aspects.

[0023] What is claimed is:
CLAIMS

1. A system for laser cutting at least one glass article comprising a pulsed laser assembly and a glass support assembly configured to support the glass article during laser cutting within the pulsed laser assembly, wherein the pulsed laser assembly comprises

   at least one non-diffracting beam (NDB) forming optical element configured to convert an input beam into a quasi-NDB beam; and

   at least one beam transforming element configured to convert the quasi-NDB beam into multiple quasi-NDB sub-beams spaced apart a distance of about 1 µm to about 500 µm;

   wherein the pulsed laser assembly is oriented to deliver one or more pulses of multiple quasi-NDB sub-beams onto a surface of the glass article, wherein each pulse of multiple quasi-NDB sub-beams is operable to cut a plurality of perforations in the glass article.

2. The system of claim 1 further comprising at least one collinnating lens configured to narrow the quasi-NDB beam from the at least one NDB forming optical element.

3. The system of claim 2 wherein the beam transforming element is oriented downstream of the collinnating lens.

4. The system of claim 2 or 3 wherein the beam transforming element is oriented proximate a Fourier-transform plane produced by the collinnating lens.

5. The system of claim 1 further comprising at least one additional collinnating lens downstream of the beam transforming element and configured to focus the multiple quasi-NDB sub-beams.

6. The system of claim 5 wherein the beam transforming element is oriented within a focal length of the additional collinnating lens.
7. The system of any of the preceding claims wherein the input beam is a Gaussian beam.

8. The system of any of the preceding claims wherein the multiple quasi-NDB sub-beams are parallel to one another and spaced apart a distance of about $1 \mu m$ to about $20 \mu m$.

9. The system of any of the preceding claims wherein the beam transforming element is chosen from a phase grating, an amplitude grating, or combinations thereof, and the NDB forming optical element is chosen from an axicon, a spatial light modulator, an elliptical lens, or combinations thereof.

10. The system of any of the preceding claims wherein the beam transforming element is configured to shift a phase of at least one of the multiple quasi-NDB sub-beams from about $\pi /4$ to about $2\pi$.

11. The system of any of the preceding claims wherein the quasi-NDB beam is a Bessel beam, an Airy beam, a Weber beam, or a Mathieu beam.

12. A method of laser cutting at least one glass article comprising:

   feeding the at least one glass article to a pulsed laser system that produces multiple quasi-non-diffracting beams (NDB) spaced apart a distance of about $1 \mu m$ to about $500 \mu m$ for every pulse;

   laser cutting the at least one glass article using the multiple quasi-NDB sub-beams to achieve a plurality of perforations in the glass article; and

   separating the glass article along the plurality of perforations to yield a laser cut glass article.

13. The method of claim 12 wherein the pulsed laser system comprises at least one NDB forming optical element configured to convert an input beam into a quasi-NDB beam, and at least one beam transforming element configured to convert the quasi-NDB beam into the multiple quasi-NDB sub-beams.
14. The method of claim 13 wherein the beam transforming element is chosen from a phase grating, an amplitude grating, or combinations thereof, and the NDB forming optical element is chosen from an axicon, a spatial light modulator, elliptical lens, or combinations thereof.

15. The method of any of claims 12-14 wherein a phase of at least one of the multiple quasi-NDB sub-beams is shifted from about $\pi/4$ to about $2\pi$.

16. A system for laser cutting at least one glass article comprising a pulsed laser assembly and a glass support assembly configured to support the glass article during laser cutting within the pulsed laser assembly, wherein the pulsed laser assembly comprises

- at least one axicon configured to convert a Gaussian beam into a Bessel beam;
- first and second collimating lenses disposed downstream of the axicon; and
- at least one beam transforming element oriented between the first and second collimating lenses, wherein the at least one beam transforming element is configured to convert the Bessel beam into multiple sub-Bessel beams which are parallel and spaced apart a distance of about 1 $\mu m$ to about 500 $\mu m$;

wherein the pulsed laser assembly is oriented to deliver one or more pulses of multiple sub-Bessel beams onto a surface of the glass article, wherein each pulse of multiple sub-Bessel beams is operable to cut a plurality of perforations in the glass article.

17. The system of claim 16 wherein the beam transforming element is a phase grating, an amplitude grating, or combinations thereof.

18. The system of claim 16 or 17 wherein the multiple quasi-NDB sub-beams are spaced apart a distance about 1 $\mu m$ to about 20 $\mu m$. 
19. The system of any of claims 16-18 wherein the beam transforming element is oriented proximate a Fourier-transform plane produced by the first collimating lens.

20. The system of any of claims 16-19 wherein the beam transforming element is oriented within a focal length of the second collimating lens.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. C03B33/02 B23K26/067 B23K26/064 B23K26/0622
ADD. B23K103/00

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C03B B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal , WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>EP 2 202 545 AI (KARLSRUHER INST TECHNOLOGIE [DE]) 30 June 2010 (2010-06-30) paragraphs [0005], [0006], [0027]</td>
<td>1-20</td>
</tr>
</tbody>
</table>

[X] Further documents are listed in the continuation of Box C.  
[X] See patent family annex.

* Special categories of cited documents :  
  "A" document defining the general state of the art which is not considered to be of particular relevance  
  "E" earlier application or patent but published on or after the international filing date  
  "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)  
  "O" document referring to an oral disclosure, use, exhibition or other means  
  "P" document published prior to the international filing date but later than the priority date claimed  

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention  
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone  
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art  
"Z" document member of the same patent family

Date of the actual completion of the international search  
16 February 2016

Name and mailing address of the ISA/  
European Patent Office, P.B. 5818 Patentlaan 2  
NL-2280 HV Rijswijk  
Tel. (+31-70) 340-2040;  
Fax: (+31-70) 340-3016

1

Date of mailing of the international search report  
23/02/2016

Authorized officer  
Marrec, Patrick
<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>us 2011/240611 Al (SANDSTROEM TORBJOERN [SE]) 6 October 2011 (2011-10-06) figures 4A-4C</td>
<td>1-20</td>
</tr>
<tr>
<td>X</td>
<td>us 2010/326138 Al (KUMATANI ISSEI [JP] ET AL) 30 December 2010 (2010-12-30) figures 12, 13</td>
<td>1-20</td>
</tr>
<tr>
<td>Patent document cited in search report</td>
<td>Publication date</td>
<td>Patent family member(s)</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-----------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>EP 2202545</td>
<td>30-06-2010</td>
<td>NONE</td>
</tr>
<tr>
<td>US 6016223</td>
<td>18-01-2000</td>
<td>NONE</td>
</tr>
<tr>
<td>US 2013334185</td>
<td>19-12-2013</td>
<td>CN 103506759 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DE 102013211024 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2013255944 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KR 20130140561 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TW 201400221 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2013334185 AI</td>
</tr>
<tr>
<td>US 2005115938</td>
<td>02-06-2005</td>
<td>CN 1616179 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2005144487 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2005115938 AI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2007205187 AI</td>
</tr>
<tr>
<td>us 2011240611</td>
<td>06-10-2011</td>
<td>EP 2542943 A2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2013521131 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2011240611 AI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wo 2011107602 A2</td>
</tr>
<tr>
<td>us 2010326138</td>
<td>30-12-2010</td>
<td>CN 101935156 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KR 20110001948 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TW 201105445 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2010326138 AI</td>
</tr>
</tbody>
</table>