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(71) Applicant (*for all designated States except US*): UNIVERSAL CRYSTAL LTD. [IL/IL]; P.O. Box 351, Industrial Zone, 21613 Carmiel (IL).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): DMITRIEV, Vladimir [RU/RU]; Apartment 227, 32 Kazakov Street, St. Petersburg, 195268 (RU). GULETSKY, Nikolay [RU/RU]; Apartment 232, 82 Metallistov Avenue, St. Petersburg, 195268 (RU). OSHEMKOV, Sergey [RU/RU]; Apartment 29, 14 Shakmatov Street, St. Petersburg, 198904 (RU).

(74) Agents: COLB, Sanford, T. et al.; Sanford T. Colb & Co., P.O. Box 2273, 76122 Rehovot (IL).

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(54) Title: MATERIAL PROCESSING APPLICATIONS OF LASERS USING OPTICAL BREAKDOWN

(57) Abstract

New methods for laser material processing in optically transparent materials are described using the volume optical breakdown phenomenon. This occurs when ultra–short pulses of the order of tens of picoseconds or less, are focused into the volume of the material by means of a high quality focusing objective lens. A focal spot close to the diffraction limit for the laser wavelength is obtained within the material. A number of processing techniques are described which are impossible to perform with hitherto available methods, including ultra–fine hole drilling, ultra–fine cutting processes, ultra–fine resolution marking or image formation applied to the interior of a sample, including diamonds, and the formation of deep black images in plastic materials.

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MATERIAL PROCESSING APPLICATIONS OF LASERS USING OPTICAL BREAKDOWN

FIELD OF THE INVENTION

The present invention relates to the field of the laser processing of materials by means of optical breakdown phenomena in the materials, especially using lasers with ultra-short pulse widths.

BACKGROUND OF THE INVENTION

There is well known in the prior art methods whereby internal marking of transparent material is performed by means of the focusing of high intensity laser pulses inside the volume of the material, such that optical breakdown takes place, causing the breakdown and disintegration of the material at an atomic level. This process is caused by effects which occur when the power density of the focused beam far exceeds the threshold above which non-linear effects occur in the transmission properties of the otherwise transparent materials, and the material strongly absorbs the focused beam.

This process has been described under various names in the prior art. The effect was first described by V.V. Agadjanov et al. in USSR Inventor's Certificate No. 321422 entitled "Process for Making Decorative Articles", issued on January 18, 1972, which described the formation of three dimensional images within the volume of transparent materials by means of highly focused Q-switched solid state lasers. In that publication, the authors use the term "heat treatment" to describe what they thought was the physical basis of the effects which they obtained. Subsequent publications have shown, however, that in all probability, the effects obtained using the laser parameters and focusing means described therein, cannot be ascribed to simple local heat treatment, but are in fact only obtained when the volume optical breakdown threshold of the material is exceeded.

In U.S. Patent No. 5,206,496, to R.M. Clement et al, entitled "Sub-surface Marking" issued on April 27, 1993, a similar process is described, but the inventors use the term "localized ionization" to describe the process whereby an opaque mark is formed within the volume of the material. Like the previously mentioned prior art, it would seem clear from a description of the technical parameters and physical results obtained that the effect is indeed one of optical breakdown and not a simple ionization process, which can take place at much lower power density levels than those described, at which levels, no visible effects are produced on the material.

Subsequent patents, such as USSR Patent No. SU 1,838, 163 to P.V. Agrynsky et al. entitled "Process for Forming Images", and Russian Patent No. RU 2,008,288 to S.V. Oshemkov, one of the current applicants, entitled "Process for Laser Forming of Images in Solid Media" describe further aspects of the process of the formation of decorative images and pictures within the volume of transparent materials, but they use what are probably correct physical terms to describe the phenomenon, namely "optical breakdown" and "volume breakdown" respectively.

Much other prior art has been subsequently published, describing more variations of the same technology. A common factor of all of the prior art known to the applicants is that the processes are all concerned with decorative or informative image production within the volume of materials which are optically transparent generally in the visible region of the spectrum. Examples of such prior art are U.S. Patent No. 4,092,518 to R.R. Merard entitled "Method of decorating a transparent plastics material article by means of a laser beam", U.S. Patent No. 4,467,172, entitled "Method and apparatus for engraving diamonds with permanent identification markings", U.S. Patent No. 5,575,936 to B. Goldfarb entitled "Process and apparatus for etching an image within a solid article", U.S. Patent No. 5,637,244 to A.I. Erokhin, entitled "Method and apparatus for creating an image by a pulsed laser beam inside a transparent material", U.S.

Patent No. 4,467,172 to J.Ehrenwald entitled "Method and apparatus for laser engraving diamonds with permanent identification markings", U.S. Patent No. 5,656,186 to G.Mourou et.al entitled "Method for controlling configuration of laser induced breakdown and ablation", German Patent Application No. DD 237972 A3 to G.Wiederhold et.al. entitled "Method for inscribing information in the body of homogeneous plastics material by means of controlled laser pulse" and U.S. Patent No. 5,761,111 to E.N.Glezer entitled "Method and apparatus providing 2-D/3-D optical information storage and retrieval in transparent materials" which deals with the application of the optical breakdown marking method for data storage, as well as many others.

To the best of the applicant's knowledge, in contrast to marking or image production techniques, there does not exist any prior art which describes the use of volume optical breakdown in true material processing techniques, as used in industrial applications, such as cutting and drilling. This definition of the term "material processing", which is commonly used in industrial laser terminology (where it also includes welding) is assumed throughout this patent specification. There therefore exists a serious need for new methods for industrial and other applications of optical volume breakdown phenomena in suitable materials.

The disclosures of all publications mentioned in this section and in the other sections of the specification, and the disclosures of all documents cited in those publications, are hereby incorporated by reference.

SUMMARY OF THE INVENTION

The present invention seeks to provide new methods for material processing using the volume optical breakdown phenomenon in optically transparent materials. This phenomenon occurs when the beam from a laser emitting ultra-short pulses of the order of tens of picoseconds or less, is focused into the volume of the material to be processed by means of a high quality focusing objective lens, such that a focal spot close to the diffraction limit for the laser wavelength is obtained within the material. Such short, high peak power pulses can be obtained for example, from temporally compressed backward stimulated Brillouin scattering (SBS) Nd:YAG lasers..

At such high power densities, of the order of 10^{13} watts/cm^2, the material undergoes optical breakdown, since the transmission limit of linear response to power is exceeded in the material, which then strongly absorbs the laser radiation. Because of the intense power density, atomic and molecular bonds of the material are broken down, and the material decomposes almost instantaneously into its most basic components, generally highly ionized component atoms.

The use of the phenomenon of optical volume breakdown enables a number of processing techniques to be carried out which were impossible to perform with hitherto available methods.

There is thus provided, in accordance with a preferred embodiment of the present invention, a method whereby ultra-fine resolution marking or image formation can be applied to the interior of a transparent sample. The marking or image can be applied in one plane within the interior of the material, or with a true three dimensional effect. The use of longer pulse lengths, of the order of tens of nanoseconds, as used in previously available techniques, such as are described in U.S. Patent No. 5,206,496, to R.M. Clement et al., results in microcracking, because of the concomitant local micro-heating of the material at the point of focus. The mark dimensions are thus correspondingly larger. According to the method of the present invention, because of the very short duration of the pulses, preferably two to three orders of magnitude shorter, the total energy per pulse is much reduced, and the only physical effect operative on the material is that of optical volume breakdown, resulting in a mark size not much larger than the diffraction limited focal spot size. The method of the present invention is thus particularly advantageous in the marking of diamonds, where it is important that the markings be invisible to the naked eye.

When an image is produced by means of the method according to this embodiment, because of the very small size of the marked points, a very large number must be marked in order to produce a complete image. This is particularly so when a three-dimensional image is formed. Previously described methods in the prior art describe the use of computer controlled x-y-z motion systems, on which the transparent sample sits during image formation. For the extremely high marking rates necessary to provide an acceptable production rate for the method of this embodiment, such a system is far too slow, and a method for producing optical breakdown laser marking at high rates must be used.

There is therefore also provided, in accordance with yet another preferred embodiment of the present invention, a method whereby optical breakdown marking and image formation in transparent materials is performed by angular scanning of the laser beam in synchronization with the output pulse program of the pulsed laser. The scanner may be of the galvanometer, acousto-optic or rotating mirror type, or any other suitable high speed angular scanning device, capable of keeping the beam positioning mechanism in synchronization with the high rate of the beam marking process.

One of the drawbacks of the previously described methods of marking or image formation within transparent materials using laser methods, is that it is not known how to obtain black markings in plastic. By varying the pulse width and energy it is possible to obtain various shades of gray, ranging from a mere diffuseness of the originally transparent material at the marked spot, through to a dark gray color. In accordance with a further preferred embodiment of the present invention, there is also provided a method whereby, by selection of the correct type of plastic, and by use of the correct laser and focusing parameters to ensure optical breakdown, true black markings and images can be obtained.

There is further provided, in accordance with another preferred embodiment of the present invention, a method whereby materials which are opaque to visible light but transparent in the near infra-red can be marked internally with a very high resolution identifying mark that can be read using a near infra-red source of radiation. Like the previous described embodiment, this embodiment uses the volume optical breakdown effect to write within the bulk of the wafer, a very high resolution mark using a laser wavelength to which the semiconductor material is transparent.

In accordance with yet another preferred embodiment of the present invention, there is further provided, a method for drilling ultra-fine holes in transparent materials. A prior art method for drilling parallel holes has been described by T.R. Anthony in U.S. Patent No. 4,473,737. Using Q-switched Nd:YAG laser pulses of 200 nsec. duration, holes of diameter 25 μm are obtained in 0.33mm thick sapphire wafers, for use in the semiconductor industry. The holes are drilled with only a slight taper by means of reverse drilling from the far side of the wafer towards the near side, far and near being relative to the impingement surface of the laser beam. The method of reverse drilling using such lasers is well known in laser diamond processing, where it is used for drilling a debris removal hole to a pique, before laser evaporation of the pique. Such holes are generally drilled from the far surface of the stone to minimize damage to the stone during drilling.

According to a preferred method of the present invention, by using the volume optical breakdown effect in the material to be drilled, it becomes possible to produce very fine holes by means of reverse drilling, and with diameters of the same order of magnitude as the focal size of the laser drilling beam. Furthermore, it is possible, using the method of the present invention to drill holes and channels in any direction, including non-straight holes, such as a meandering path.

In accordance with yet another preferred embodiment of the present invention, there is further provided a method for ultra-fine cutting of transparent materials. The method can be similar to that described in the above mentioned drilling embodiment, but including the further step of drilling further holes closely spaced to each other such that a continuous cut channel is produced.

Alternatively and preferably, the focused laser beam is made to execute multiple traverses of the material to be cut, first of all at the surface of the material, and slowly working down through the material with a sawing motion, to produce a complete cut channel, which can extend right through the thickness of the material if desired.

In accordance with yet another preferred embodiment of the present invention, there is provided a method of performing material processing on a material substantially transparent to a laser radiation, and consisting of the steps of focusing pulses of the laser radiation into the volume of the material, the pulses being such that the material undergoes optical breakdown, and moving the focal point of the pulses of the laser radiation relative to the material according to a predetermined path.

There is further provided in accordance with yet another preferred embodiment of the present invention a method as described hereinabove and wherein the material processing is a drilling process or an industrial marking process.

In accordance with still another preferred embodiment of the present invention, there is provided a method as described hereinabove and wherein the material is opaque to visible wavelengths.

There is further provided in accordance with still another preferred embodiment of the present invention a method as described hereinabove and wherein the predetermined path is a three dimensional path.

In accordance with a further preferred embodiment of the present invention, there is also provided a method as described hereinabove and wherein the material is a glass, a plastic, a gemstone, or a semiconductor.

There is provided in accordance with yet a further preferred embodiment of the present invention a method as described hereinabove and wherein the moving of the focal point of the pulses of the laser radiation relative to the material according to a predetermined path is accomplished by means of a three axis mechanical motion system, an angular scanning system, or a combination of both.

There is even further provided in accordance with a preferred embodiment of the present invention a method as described hereinabove and wherein the moving the focal point of the pulses of the laser radiation relative to the material according to a predetermined path is synchronized in a predetermined manner with the emission of the pulses of the laser radiation.

Furthermore, in accordance with yet another preferred embodiment of the present invention, there is provided a method of forming images in a material substantially transparent to a laser radiation, and consisting of the steps of focusing pulses of the laser radiation into the volume of the material, the pulses being of width shorter than 100 picoseconds, and of pulse energy and power density such that the material undergoes optical breakdown in micro-zones, without the formation of radial cracks, and moving the focal point of the pulses of the laser radiation relative to the material according to a predetermined path.

There is also provided in accordance with a further preferred embodiment of the present invention a method as described hereinabove and wherein the predetermined path is a three dimensional path.

In accordance with yet another preferred embodiment of the present invention, there is provided a method as described hereinabove and wherein the material is a glass, a plastic or a gemstone.

There is further provided in accordance with yet another preferred embodiment of the present invention a method as described hereinabove and wherein the moving of the focal point of the pulses of the laser radiation relative to the material according to a predetermined path is accomplished by means of a three axis motion system, an angular scanning motion system, or a combination of both.

In accordance with still another preferred embodiment of the present invention, there is provided a method of forming black images inside the volume of a plastic material containing carbon, the plastic material being substantially transparent to laser radiation, and consisting of the steps of focusing pulses of the laser radiation into the volume of the plastic material, the pulses being such that the material undergoes optical breakdown, and moving the focal point of the pulses of the laser radiation relative to the plastic material according to a predetermined path.

There is further provided in accordance with still another preferred embodiment of the present invention a method of forming images inside the volume of a material opaque to visible radiation and substantially transparent to a laser radiation, and consisting of the steps of focusing pulses of the laser radiation into the volume of the material, the pulses being of width shorter than 100 picoseconds, such that the material undergoes optical breakdown, and moving the focal point of the pulses of the laser radiation relative to the material according to a predetermined path.

In accordance with a further preferred embodiment of the present invention, there is also provided a method as described hereinabove and wherein the predetermined path is a three dimensional path.

There is provided in accordance with yet a further preferred embodiment of the present invention a method as described hereinabove and wherein the material is a glass, a plastic, or a semiconductor.

There is even further provided in accordance with a preferred embodiment of the present invention a method as described hereinabove and wherein the semiconductor is silicon or gallium arsenide.

Furthermore, in accordance with yet another preferred embodiment of the present invention, there is provided a method of drilling a hole through a sample of material substantially transparent to a laser radiation, and consisting of the steps of focusing pulses of the laser radiation through the volume of the sample, onto a location close to the surface of the sample further from the surface on which the laser radiation impinges, the pulses being of width shorter than 100 picoseconds, such that the material of the sample undergoes optical breakdown and produces a first hole, short in length compared with the thickness of the sample, and which breaks out of the surface of sample further from the surface on which the laser radiation impinges, moving the focal point of the pulses of the laser radiation back towards the surface on which the laser radiation impinges, by a predetermined distance, such that a second hole is produced by the optical breakdown of the material, the predetermined distance being such that the second hole just enters the first hole, and repeating the previous step until the first and second holes produce a continuous hole through the complete thickness of the sample.

There is also provided in accordance with a further preferred embodiment of the present invention a method as described hereinabove and wherein the material is a glass, a plastic, a semiconductor, or a gemstone.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

According to one preferred embodiment of the invention, a method is described of producing ultra-fine resolution marking or image formation in the interior of a transparent sample. A temporally compressed backward stimulated Brillouin scattering (SBS) Nd:YAG laser source is used, which can typically provide up to 1mJ pulses of 20 psec. width at a wavelength of 630 nm. A high quality focusing lens system is preferably used, enabling a spot size of the order of 1μm to be obtained. According to this preferred embodiment of the invention, the object to be marked is moved to produce a complete marking sequence or image. If the motion is performed in only one direction, the trivial case of an inscribed line is obtained. If only two-axis motion is used, the marking or image is applied in a plane within the interior of the material. If all three axes are used, or alternatively, two axes and a rotation, a true three dimensional image is obtained within the volume of the object.

Because of the very short duration of the pulses, the total energy per pulse needed for bulk optical breakdown need be no more than 1 μJ or even less, and the only physical effect operative on the material is that of optical volume breakdown, resulting in a mark size not much larger than the diffraction limited focal spot size. The mark, at these pulse widths and pulse energies, shows no sign of radial microcracking due to local heating effects, with its accompanying widening effect, such as is obtained with the previously described technology using longer pulse lasers. As a result, the method of the present invention enables ultra-fine marks to be applied within the interior of the sample, with mark widths only slightly larger than the size of the diffraction limited focal spot size, this being of the order of 1μm. The method can be applied to any material substantially transparent to the laser wavelength, such as plastics or glass, and semi-precious or precious gemstones including diamonds.

The use of a computer controlled three-axis x-y-z or x-y-θ motion system, on which the transparent sample sits during image formation, makes the production of a complete three dimensional image by the above described method a comparatively slow process. There are ultrashort lasers with pulse repetition rates up to 1000 Hz, and since this exceeds the slew rate of typical CNC-controlled mechanical motion systems, even for the very small steps required between marked points, the process is motion system limited.

According to another preferred embodiment of the invention, a method is described of producing the relative motion of the sample and the focused laser beam producing the optical breakdown marking or image formation by means of angular scanning of the laser beam in synchronization with the output pulse program of the pulsed laser. In one preferred embodiment, the scanner is of the galvanometer type, but acousto-optic or rotating mirror types, or any other suitable high speed angular scanning device may be used, on condition that it is capable of keeping the beam positioning mechanism in synchronization with the high rate of the beam marking process. By the use of such a galvanometer scanning method, a three dimensional image, produced in a glass block using the ultra-fine marking method of the first embodiment described hereinabove, which took 20 minutes to produce on a 3-axis motion system, could be completed in only about 2 minutes when executed using the method of this described embodiment.

A further method of the use of volume optical breakdown in material processing is that of forming truly black images and marks in plastic materials.

Such internal markings or images are essential in many high resolution optical components, which require good optical contrast effects by the use of a true black marking technique. The use of the method described in this preferred embodiment allows the production of such components at low cost, and yet with very high precision, on plastic components, where previously, they had to be manufactured in glass by comparatively costly graticule technology methods.

The methods consists of the steps of focusing an ultra-short pulse width laser, such as that with the characteristics described above, onto the plastic optical part, and then moving the part in synchronization with the laser pulse output according to a predetermined program, thereby producing the required marking pattern or image. The type of plastic used must be determined by experiment, since not all transparent plastics produce a strong black color. It seems that those plastics which absorb ultra-violet radiation strongly, may produce the best black markings. It is thought that this is due to the effect on the plastic of the ultra violet radiation produced by the plasma formed during the optical breakdown process in the plastic. Plastics which absorb the UV radiation well, carbonize well, thus producing strong black coloring.

According to another preferred embodiment of the present invention, a method is described whereby a material which is opaque to visible light but transparent in the near infra-red can be marked internally with a very high resolution identifying mark that can be read using a near infra-red source of radiation. The method consists of the steps of focusing an ultra-short pulse width laser, such as that described in the methods of the previous embodiments, into the sample to be marked, followed by the step described above of moving the sample and laser beam in synchronization with the laser pulsing rate, such as to form the desired mark.

This method is particularly useful in the semiconductor industry, where a need exists to mark silicon or gallium arsenide wafers with very high resolution identifying marks, and without doing so on the surface of the wafer, where the debris of a surface marking process would be detrimental to the level of cleanliness required in many of the wafer processing stages. Though marks can be applied by conventional microlithographic methods using photoresist and etching procedures, the internal laser marking method is vastly quicker, and is a simple one stage process, unlike the microlithographic method. Furthermore, the use of an internal marking method, such as that described in this embodiment of the present invention, leaves the surface of the wafer uncluttered with superfluous features. This advantage of this embodiment of the present invention becomes even more important when marking has to be applied at a chip level, rather than at a wafer level, since chip real estate is such a high value commodity. In the case of silicon, which is substantially transparent from about 1.1 μm to almost 5 μm, a laser emitting pulses at 1.9 μm is suitable for implementing the method of this embodiment.

A further method according to another preferred embodiment of the present invention, is that of using the volume optical breakdown effect to drill very parallel ultra-fine holes in transparent samples by means of a reverse drilling procedure. The method consists of the steps of first focusing an ultra-short pulse width laser, such as that described in the first preferred embodiment above, just inside the further surface of the sample through which the hole is to be drilled, and of firing a predetermined number of pulses. The volume optical breakdown incurred causes a narrow void or hole to be drilled, with the debris being ejected forward, in the beam direction, and away from the sample. It is known that in this method, the interaction mechanism of the laser with the material is that of optical breakdown, since a plume of plasma is seen ejected from the front end of the drilled hole. The void formed has a diameter of the same order of magnitude as the focal size of the laser drilling beam, and is typically only 1μm in plastic materials, or 2 μm to 3 μm in more refractory materials such as glass or sapphire.

In the next step, the focal position of the laser is moved back a distance of 0.1 - 10 μm, depending on the material and another series of pulses is fired. This extends the void to join the already existent void. In this way, a complete hole is drilled through the sample by means of optical breakdown interactions. Since the hole is reverse drilled, the ejected debris, plasma and gases do not cause the hole to be widened as it is drilled, and good parallelism and high uniformity of bore size can thus be obtained.

If good parallelism or uniform bore size are required in straight holes, a further physical mechanism is operative to assist in achieving these objectives if the hole is drilled by the method of this invention. Because of the non-linear effects of the very high intensity laser radiation on the lattice, the refractive index of the material being drilled is dependent on the intensity of the beam falling on it. It is well known that at very high field intensities, the refractive index rises with field intensity. Since the intensity of the beam is higher in the center of the hole than at its edges, the refractive index is also higher in the center. As a result, a self-focusing effect takes place as the drilling proceeds, and this mechanism assists in keeping the hole parallel and of accurately contained size through its whole length.

By this method, 3 μm holes can be typically drilled right through a 0.5 mm thickness of glass. Such holes are, to the best of the applicants' knowledge, a complete order of magnitude smaller than those capable of being produced by previously available techniques, and can thus be used, for instance, for the production of high-strength micron-pored filter elements in materials such as glass and quartz.

According to another preferred embodiment of the present invention, a method of microscopic cutting of such transparent materials is provided, whereby a number of holes are drilled sufficiently closely spaced to each other, that adjacent bores run into each other, resulting in the production of a continuous cut channel according to a predetermined path.

Alternatively and preferably, the focused laser beam is made to execute multiple traverses of the material to be cut, according to a predetermined path, the first traverse being at the surface of the material, and then slowly working down through the material with a sawing motion, to produce a complete cut channel, which can extend right through the thickness of the material if desired.

Alternatively, the cut can be commenced at the far surface of the sample, and the sawed channel moved up through the sample towards the laser impingement surface. These methods of cutting, according to the present invention, are particularly advantageous in diamond processing, where a minimum of material is removed, and in the semiconductor industry, where there is a need to cut extremely fine and smooth channels. The use of these methods enables a smooth cut of width less than 10 μm to be produced through a thickness of 0.2 mm. of glass.

It will be appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described hereinabove. Rather the scope of the present invention includes both combinations and subcombinations of various features described hereinabove as well as variations and modifications thereto which would occur to a person of skill in the art upon reading the above description and which are not in the prior art.

CLAIMS

We claim:

1. A method of performing material processing on a material substantially transparent to a laser radiation, and comprising the steps of:

focusing pulses of said laser radiation into the volume of said material, said pulses being such that the material undergoes optical breakdown; and

moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path.

2. The method of claim 1 and wherein said material processing is a drilling process.

3. The method of claim 1 and wherein said material processing is a marking process.

4. The method of claim 1 and wherein said material processing is a cutting process.

5. The method of claim 1 and wherein said material is opaque to visible wavelengths.

6. The method of claim 1 and wherein said predetermined path is a three dimensional path.

7. The method of claim 1 and wherein said material is selected from the group consisting of a glass, a plastic, a gemstone and a semiconductor.

8. The method of claim 5 and wherein said material is a semiconductor.

9. The method of claim 1 and wherein said moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path is accomplished by means of a mechanical motion system.

10. The method of claim 1 and wherein said moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path is accomplished by means of a scanning system.

11. The method of claim 1 and wherein said moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path is accomplished by means of a combination of a mechanical motion system and a scanning system.

12. The method of claim 1 and wherein said moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path is synchronized in a predetermined manner with the emission of said pulses of said laser radiation.

13. A method of forming images in a material substantially transparent to a laser radiation, and comprising the steps of:

focusing pulses of said laser radiation into the volume of said material, said pulses having a pulse width shorter than 100 picoseconds, and a pulse energy and power density such that said material undergoes optical breakdown in micro-zones, without the formation of radial cracks; and

moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path.

14. The method of claim 13 and wherein said predetermined path is a three

dimensional path.

15. The method of claim 13 and wherein said material is selected from the group consisting of a glass, a plastic and a gemstone.

16. The method of claim 13 and wherein said moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path is accomplished by means of a mechanical motion system.

17. The method of claim 13 and wherein said moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path is accomplished by means of an angular scanning motion system.

18. The method of claim 13 and wherein said moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path is accomplished by means of a combination of a mechanical motion system and an angular scanning motion system.

19. A method of forming black images inside the volume of a plastic material containing carbon, said plastic material being substantially transparent to a laser radiation, and comprising the steps of:

focusing pulses of said laser radiation into the volume of said plastic material, said pulses being such that the material undergoes optical breakdown; and

moving the focal point of said pulses of said laser radiation relative to said plastic material according to a predetermined path.

20. A method of forming images inside the volume of a material opaque to visible radiation and substantially transparent to a laser radiation, and comprising

the steps of:

focusing pulses of said laser radiation into the volume of said material, said pulses being of width shorter than 100 picoseconds, such that the material undergoes optical breakdown; and

moving the focal point of said pulses of said laser radiation relative to said material according to a predetermined path.

21. The method of claim 20 and wherein said predetermined path is a three dimensional path.

22. The method of claim 20 and wherein said material is selected from the group consisting of a glass, a plastic and a semiconductor..

23. The method of claim 22 and wherein said semiconductor is selected from the group consisting of silicon and gallium arsenide.

24. A method of drilling a hole in a sample of material substantially transparent to a laser radiation, and comprising the steps of:

focusing pulses of said laser radiation in the volume of said sample, onto a location close to the surface of said sample distant from the surface on which the laser radiation impinges, said pulses being of width shorter than 100 picoseconds, such that the material of said sample undergoes optical breakdown and produces a first void, short in length compared with the thickness of said sample; and which breaks out of said surface of sample distant from the surface on which the laser radiation impinges;

moving the focal point of said pulses towards the surface on which the laser radiation impinges, by a predetermined distance, such that a second void is produced by said optical breakdown of said material, said predetermined distance being such that said second void enters said first void; and

repeating the previous step until said first and second voids produce a continuous hole within said sample.

25. The method of claim 24 and wherein said continuous hole passes through the complete thickness of said sample.

26. The method of claim 24 and wherein said material is selected from the group consisting of a glass, a plastic, a gemstone and a semiconductor..

27. A method of cutting a sample of material substantially transparent to a laser radiation, and comprising the steps of:

drilling a hole according to the method of claim 24;

moving the position at which said laser radiation impinges on said sample in a plane perpendicular to said laser beam by a predetermined distance;

drilling a second hole in said sample, wherein said predetermined distance is such that the bore of said second hole enters the bore of said first hole; and

repeating said above steps wherein the direction of said moving of said position at which said laser radiation impinges is selected to produce a predetermined path within said sample.

28. The method of claim 27 and wherein said material is selected from the group consisting of a glass, a plastic, a gemstone and a semiconductor.

29. A method of cutting a sample of material substantially transparent to a laser beam, and comprising the steps of:

a) focusing pulses of said laser beam at a first point in the surface of said sample, said pulses being of width shorter than 100 picoseconds, such that the material of said sample undergoes optical breakdown;

b) moving the focal point of said pulses laterally in the plane of said surface of said sample according to a predetermined cutting path, to produce a first channel in said material;

c) displacing said focal point by a predetermined distance into the volume of said sample ;

d) moving said focal point of said pulses laterally in a plane parallel to the plane of said first channel, according to the same predetermined cutting path, to produce a second channel in said material, wherein said predetermined distance is such that said first and said second channels are contiguous; and

e) repeating steps c) and d) until a desired cutting depth of said sample is completed.

30. The method of claim 29 and wherein said material is selected from the group consisting of a glass, a plastic, a gemstone and a semiconductor..

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL99/00655

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :B23K 26/38
US CL : 219/121.72
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)

U.S. : 219/121.67,211.68,121.69,121.7,121.71,121.72,121.8

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,786,560 A (TATAH et al) 28 July 1998 (28/07/98), see entire document, especially column 3,lines 21-63.	1-4,6,7,9, 12 --------- 5,10,11, 13-16,20-24, 26- 30
Y	US 5,206,496 A (CLEMENT et al) 27 April 1993 (27/04/93) ,see column 5, lines 45-66.	5,10,11,18,20-23
Y	US 5,656,186 A (MOUROU et al) 12 August 1997 (12/08/97) , see entire document.	13-18, 20-24, 26-30
Y	US 5,582,752 A (ZAIR) 10 December 1996 (10/12/96), see entire document.	17

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

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"A" document defining the general state of the art which is not considered to be of particular relevance

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

"P" document published prior to the international filing date but later than the priority date claimed

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Date of the actual completion of the international search	Date of mailing of the international search report
17 FEBRUARY 2000	29 FEB 2000

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. (703) 305-3230

Authorized officer
GEOFFREY S EVANS
Telephone No. (703) 308-0661

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL99/00655

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,575,936 A (GOLDFARB) 19 November 1996 (19/11/96), see entire document.	1-30