Technical Report

Subsurface precision machining of glass substrates by innovative lasers

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At very high laser intensities, achieved with modern, diode-pumped solid-state lasers having high beam quality and high pulse power, even transparent materials such as glass can be easily machined with high efficiency and precision. Examples are given by the subsurface engraving, the cutting and the drilling of glass, where the physical effect of nonlinear absorption in transparent media is used. This enables machining processes and results which are not feasible with any other tool known before.

1. Introduction

In the past laser machining of glass was mostly limited to far-infrared or ultraviolet lasers [1 and 2]. This is due to the fact that glass absorbs laser radiation only in these wavelengths regimes (figure 1). At other wavelengths glass is highly transparent and merely a small fraction of the laser power is transformed into thermal energy – not sufficient for materials processing.

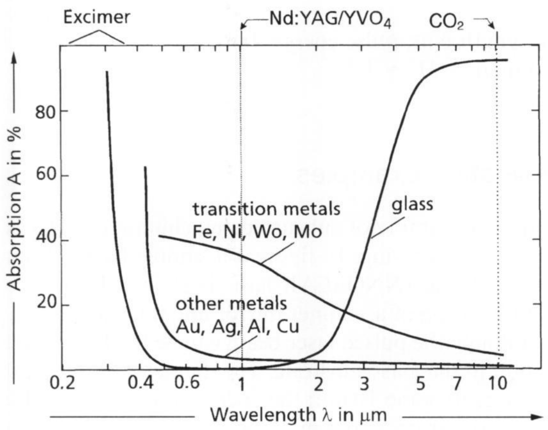

Figure 1. Absorption of different materials as a function of the wavelength.

Excimer lasers with wavelengths in the ultraviolet spectral range and CO_2 lasers with infrared radiation are absorbed in a thin sheet at the workpiece surface due to their high absorption coefficient and subsequently the glass is melted or evaporated, if high pulse energies are applied. Due to their good absorption properties excimer or CO_2 lasers are common tools for cutting, welding or surface-structuring of glasses [2 and 3].

With solid-state lasers such as Nd:YAG or Nd:YVO_4, which are widely used in industrial applications due to their advantageous properties such as compactness and simple operation, glass machining was not possible as the radiation at 1.06 μm wavelength is hardly absorbed: the laser beam gets through the glass without being weakened significantly. By using the physical effect of the nonlinear absorption, however, in combination with the modern diode-pumped solid-state lasers it has become possible for some years to machine highly transparent materials such as glasses with processes enabling entirely new opportunities.

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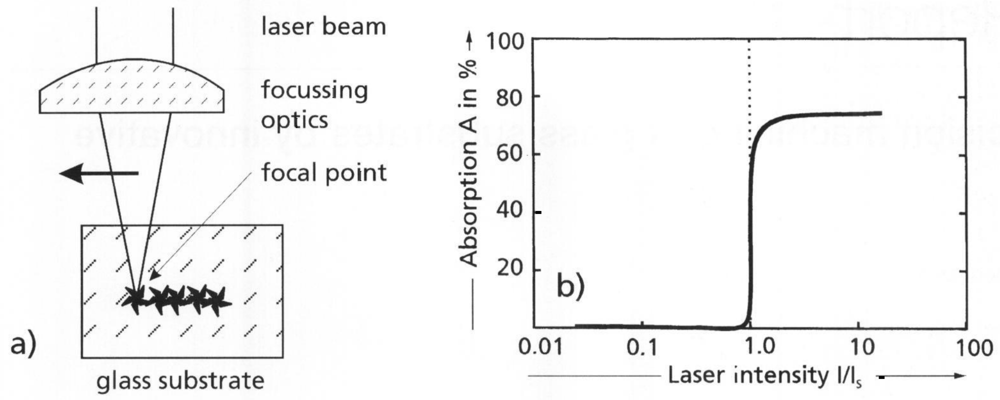
2. Principle of laser material interaction

The principle of the machining of transparent materials with solid-state laser radiation is illustrated in figure 2a: a laser beam is focussed into a transparent medium and initially gets through the material nearly unaffected, due to the negligible absorption. If the laser however is focussed to a very small spot and is emitting very short and intensive pulses, a very high intensity is achieved in the focal spot, exceeding the threshold intensity I_s as shown in figure 2b. Above this threshold intensity an electron avalanche is created, starting from a couple of free charge carriers, being always present. Due to the strongly increased charge carrier density the absorption coefficient for electromagnetic radiation abruptly increases to values of several 10 % and the laser power, thus absorbed, leads to melting and evaporation of a small amount of material. It is specific for this process that the interaction between laser and material is localized to the focal point of the laser beam, the material below and above is not affected at all.



Figures 2a and b. Nonlinear absorption of highly intensive laser radiation in transparent media; a) laser set-up, b) absorption as a function of the normalized laser intensity.

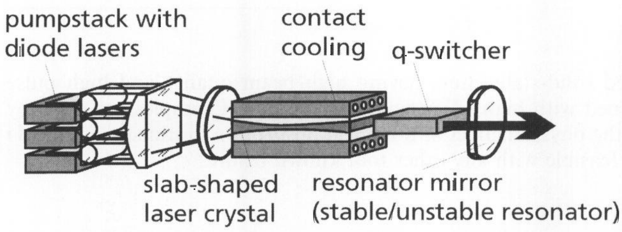


Figure 3. Scheme of the diode-pumped solid-state laser according to the INNOSLAB principle (EdgeWave GmbH); principle set-up of the laser.

The threshold intensity I_s for this nonlinear process is considerably high: it is in the range of 10^9 to 10^{10} W/cm^2. Such intensities can be achieved if two conditions are met: on the one hand a laser is required providing a high beam quality, which means that the beam can be focused down to a very small spot size, and on the other hand the laser has to be operated in a so-called q-switched mode with very high peak power. Diode-pumped, q-switched solid-state lasers combining both properties have been commercially available for some years. Common types are the Nd:YAG and the Nd:YVO_4 laser.

A particularly advantageous concept for a diode-pumped solid-state laser is the so-called INNOSLAB laser (Edge Wave GmbH, Aachen (Germany) www.edge-wave.de) [5 and 6], especially for the subsurface machining of glass, discussed in this paper. The laser material is a slab-shaped YVO_4 crystal, doped with the laser-active neodymium ion (Nd^{3+}). The slab crystal is pumped from one end by a stack of high-power diode lasers. In comparison to alternative concepts the INNOSLAB is distinguished by its high efficiency, high beam quality and high amplification, which enables the generation of exceptionally short pulses as they are needed for the subsurface machining of glass. In addition to this, the INNOSLAB is the only concept which allows in a simple way the scaling of the average laser power, while maintaining the pulse and beam quality properties needed for the subsurface machining process. Scaling of the average power is important in many commercial applications, where high numbers of pieces or large areas have to be machined at low cost.

The particular system shown in figure 3 has the specifications:

- wavelength 1.06 µm,
- electro-optical q-switch, pulse frequency 0 to 50 kHz,

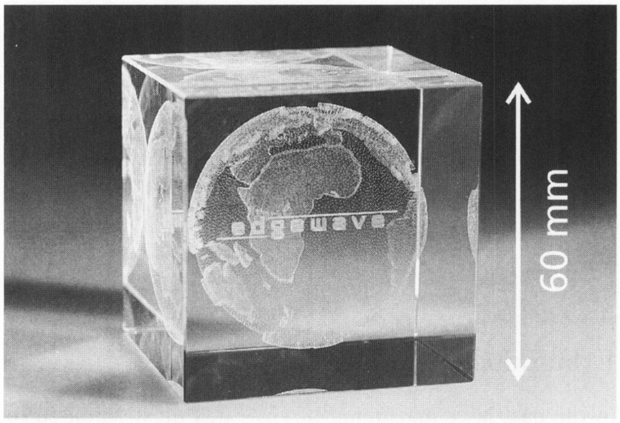


Figure 4. Subsurface engraving with a diode-pumped INNOSLAB laser of EdgeWave GmbH; the three-dimensional structure in the glass volume consists of about 40 000 dots. With a 1000 Hz laser the production time amounts to about 4 min. In this specific example the production time is dominated by the beam handling system, not by the laser.

- pulse length 6 ns, pulse energy 4 mJ,
- beam quality $M^2 < 1.5$.

3. Application examples

A well-known example of subsurface machining of glass is the subsurface engraving. In figure 4 a sample having been produced with the INNOSLAB laser is shown. By means of the combination of a scanner mirror and a linear axis for the z-coordinate the pulsed laser beam can be freely directed to any point in the glass substrate. The diameter of the focal spot amounts to some 10 µm, the energy of one laser pulse ranges typically from 2 to 3 mJ. The energy is absorbed to a great extent in the focal zone, according to the nonlinear absorption process discussed in section 2 and leads to melting and evaporation of the materials. Due to the mechanical stress associated with the melting and evaporation crack structures are induced in the glass, with a size of approximately 100 µm.

These cracks, perceived as dots by the naked eye, are arranged to three-dimensional objects in the volume of the glass block (for instance to the globe in figure 4) by appropriate control of the beam steering system. For decorative objects as the one shown in the figure, lasers are used with

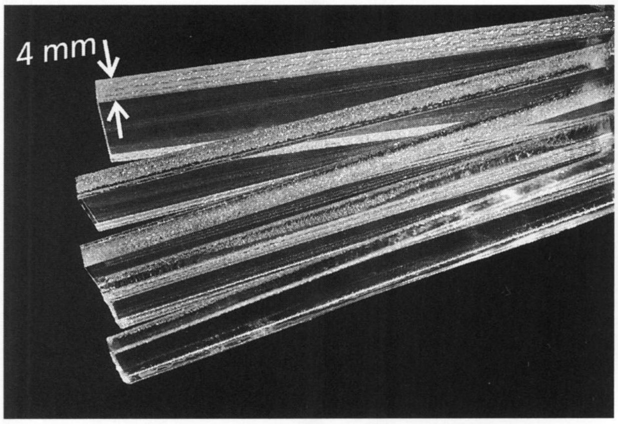


Figure 5. Cutting of sheet glass by subsurface scratching with the INNOSLAB laser. The sheet thickness was about 4 mm, the speed was 2 m/s.

a pulse rate of about 1000 Hz, engraving 1000 points per second in the glass. With the INNOSLAB laser considerably higher pulse rates of more than 10000 Hz can be achieved, thus enabling high-speed subsurface engraving of large areas for instance in sheet glass.

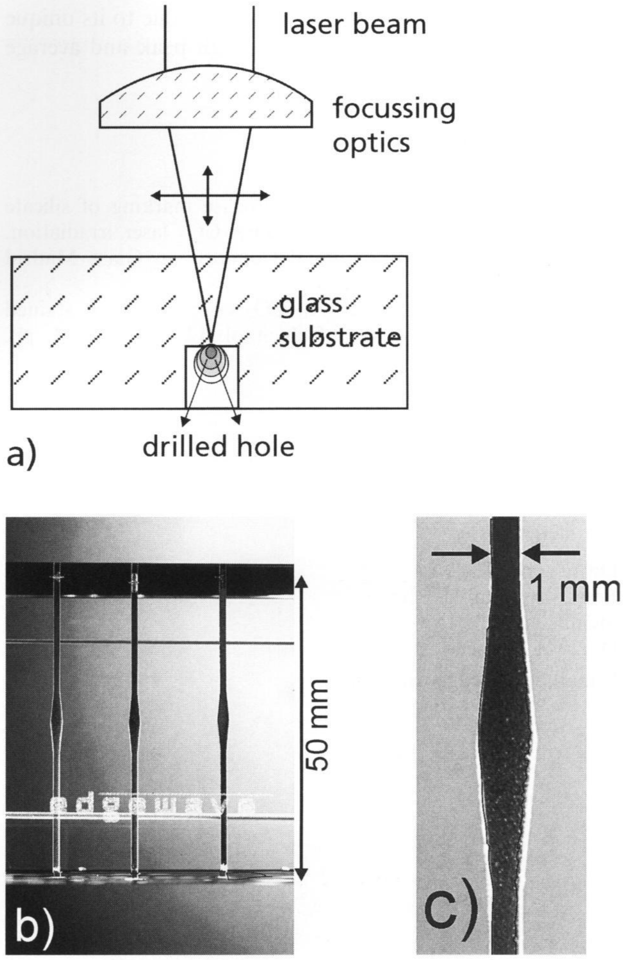
The similar process as discussed before can be used as well for high-speed cutting by surface or subsurface scratching of sheet glass, as illustrated in figure 5. Along the line to be cut a sequence of cracks is produced in the glass volume, in the vicinity of the upper or lower surface. After this process the sheet can be mechanically separated very easily. The lateral distance between the dots is in the range from 50 to 200 µm. Due to the high repetition rate of the INNOSLAB laser scratching speeds of up to 3 m/s are achievable in this way. Curved lines can be cut as well. The roughness of the cutting edges is in the range around some 10 µm. Glass sheet material of any thickness can be cut with this process.

Figures 6a to c illustrate a further innovative application of the INNOSLAB laser, where highly precise hollow structures are created in the glass with shapes which are not machinable with conventional mechanical methods. The laser beam is applied from the back of the workpiece and focused to the opposite inner surface. In contrast to the subsurface engraving and cutting process the evaporated glass material is able to freely flow away from the processing zone and by appropriate steering of the beam very precise and reproducible holes with any cross sections can be produced in the glass. This process has a couple of fundamental advantages:

a) the process is highly precise and reproducible as the outstreaming material vapour does not interact with the laser beam, which would result in a serious quality reduction due to the occurring plasma processes;

b) the depth of the hole and the aspect ratio (hole depth in relation to hole diameter), respectively, is scalable almost without limit with no loss in accuracy; figure 6b shows holes with an aspect ratio of about 50, considerably larger values are easily achievable;

c) holes can be produced with cross sections which are changing along the hole depth: the hole in figure 6c has a precise conical broadening in the middle; such boreholes can not be created with any other method;



Figures 6a to c. Precision drilling in glass: boreholes can be produced, having a depth-dependent cross section (the holes in figure b are filled with a coloured liquid to increase visibility); with the INNOSLAB laser the manufacturing time for such a hole is about 6 min; a) principle set-up, b) drilled holes, c) detail view of the hole extension in the centre of figure b.

d) due to the illustrated layer-wise removal process it is possible to create nearly any three-dimensional structure in glass and glass-like materials.

Applications for this process can be seen in the production of sieves for aggressive media, contact leadthroughs, manifolds, mixers and microreactors for chemistry and biology, as well as components for medicine, biology, fluid mechanics and hydraulics.

4. Summary and conclusion

At very high laser intensities, achieved with modern, diode-pumped solid-state lasers having high beam quality and high pulse power, even transparent materials such as glass can be easily machined with high efficiency and precision. Examples are given by the subsurface engraving, the cutting and the drilling of glass, where the physical effect of non-linear absorption in transparent media is used. This enables machining processes and results which are not feasible with any other tool known before. The INNOSLAB laser in particular offers a great potential for the economical application of these processes at large lot sizes, due to its unique combination of high beam quality, high peak and average power.

5. References

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