Technical Report

Damage-free laser micromarking of glass

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Unfortunately glass is highly transparent for the wavelength of 1.06 µm commonly used by marking systems. Absorption via nonlinear effects can circumvent this problem. There are three conditions for an effective use of nonlinear effects: high repetition rate (500 Hz), TEM_{00} beam quality ($M^2 < 1.5$) and high pulse power (>0.5 MW). Microplasma laser sputtering in particular allows marking of glass surfaces without any damage, i.e. without cracks and residual stress. Micromarking with a point distance of about 25 µm is possible. This is the equivalent of a printer resolution of 1000 dpi.

Schädigungsfreie Mikrobeschriftung von Glas

Die herkömmlich zum Beschriften eingesetzten Nd-YAG-Laser besitzen eine Wellenlänge, für die die meisten Gläser transparent sind. Bei sehr hohen Leistungsdichten (10^{10} bis 10^{12} W/cm^2) kann es aufgrund nichtlinearer optischer Effekte trotzdem zu einer Absorption der Laserenergie kommen. Mit den so entstehenden Ablationskratern (Durchmesser 25 µm) ist eine extrem lokalisierte und absolut schädigungsfreie Markierung mit einer Auflösung bis zu 1000 dpi möglich.

1. Introduction

There are several industrial applications of laser machining of transparent media and of glass in particular. The main field of these applications is sealing, cutting and marking of glass products. In the case of sealing and cutting only cw-CO_2 lasers are used. Because of high absorption at wavelength 10.6 µm and the low heat conductivity of most glass types the CO_2-laser radiation leads to local heating on a small area. The desired temperature profile can be realized by suitable beam forming or beam oscillation.

In the case of marking also TEA-CO_2 lasers and excimer lasers are used [1]. The pulse power of these lasers is high enough to induce an ablation process on relatively large areas. Therefore, mask ablation is the preferred marking technology. The marking contrast results from the change of topography and/or from the surface damage (figures 1 and 2). Low microdamage and hence low contrast is obtained with excimer lasers, owing to their short wavelength and pulse duration. Low-contrast marking is used for spectacle lens. The high-contrast marking with TEA-CO_2 lasers is used for calibration stamps on beer glasses for example.

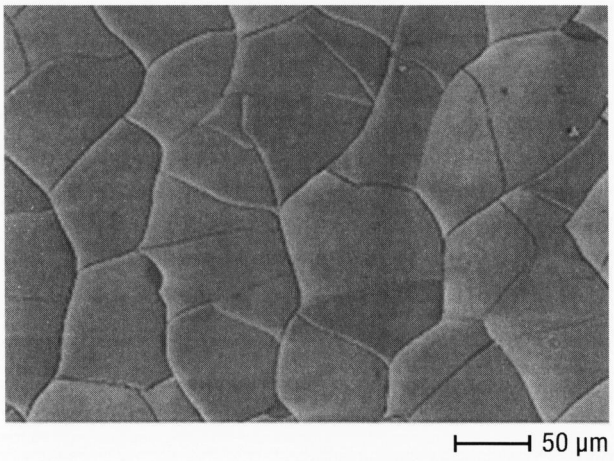

Figure 1. Glass surface irradiated with TEA-CO_2 laser (SEM image).

The main disadvantage of mask ablation technology is the low flexibility. In order to change the marking pattern, the mask has to be exchanged. Thus a programmable and individual marking is out of the question. On

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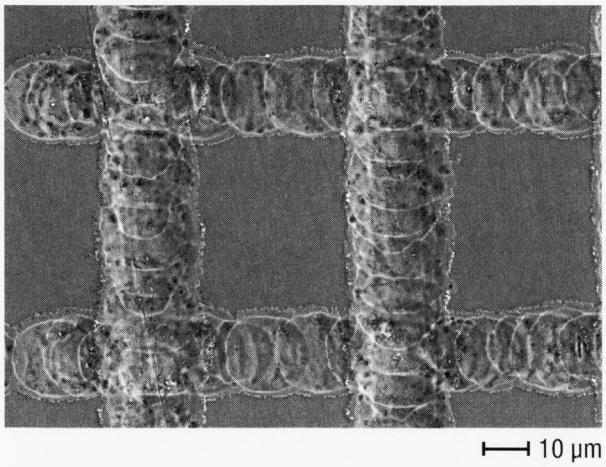


Figure 2. Glass surface patterning with excimer laser (SEM image).

the other hand, the marking of pixel-based or vector-based images by means of galvoscanner is state of the art for nontransparent media. For this technology, lasers with high beam quality and pulse repetition rate like cw-pumped solid state lasers are necessary. Unfortunately, glass is nearly perfectly transparent to the commonly used wavelength of 1.06 µm. Absorption via nonlinear effects can circumvent this problem.

2. Nonlinear effects

The so-called avalanche ionisation is a nonlinear effect which is usable for material processing. This effect results from the electric field dependence of the refractive index and from absorption via inverse Bremsstrahlung [2]. The electric field of the incident laser beam changes the real part and the imaginary part of the complex refractive index. The rise of the imaginary part is related to the occurrence of multiphoton absorption.

Power densities in the range of 10^{10} to 10^{12} W/cm^2 induce changes of refractive index in the range of 10^{-6} to 10^{-3}. Thus the laser beam profile creates a profile of the refractive index. This profile works as a focusing lens. An avalanche-like rise of power density starts. Thus the multiphoton absorption becomes more and more effective.

The free electrons induced by multiphoton absorption are able to absorb laser energy via inverse Bremsstrahlung. These hot electrons cause secondary ionisation. Hence a second avalanche-like process, the dielectric breakdown, starts associated with a dense plasma. This local plasma and the related thermal gradient result in damage or ablation of the glass in the side or on the surface. The damage threshold for optical glass [3] in case of laser pulse duration of 100, 10 and 0.1 ns can be estimated at $5 \cdot 10^9$, $1.6 \cdot 10^{10}$ and $1.6 \cdot 10^{11}$ W/cm^2.

3. Laser technology

TEM_{00} beam is necessary to achieve power densities in the range of 10^{10} to 10^{12} W/cm^2. The focusability of a laser is given by the beam parameter product (BPP):

$$\mathrm{BPP} = \frac{1}{4} \cdot w_0 \cdot \theta \tag{1}$$

where w_0 is the beam waist and θ the full angle of divergence. The beam parameter product of an ideal, that means diffraction-limited, TEM_{00} mode is:

$$\mathrm{BPP}_{\mathrm{ideal}} = \lambda/\pi \tag{2}$$

where λ is the laser wavelength. The beam quality parameter k is defined by:

$$\mathrm{BPP} = k \cdot \mathrm{BPP}_{\mathrm{ideal}} . \tag{3}$$

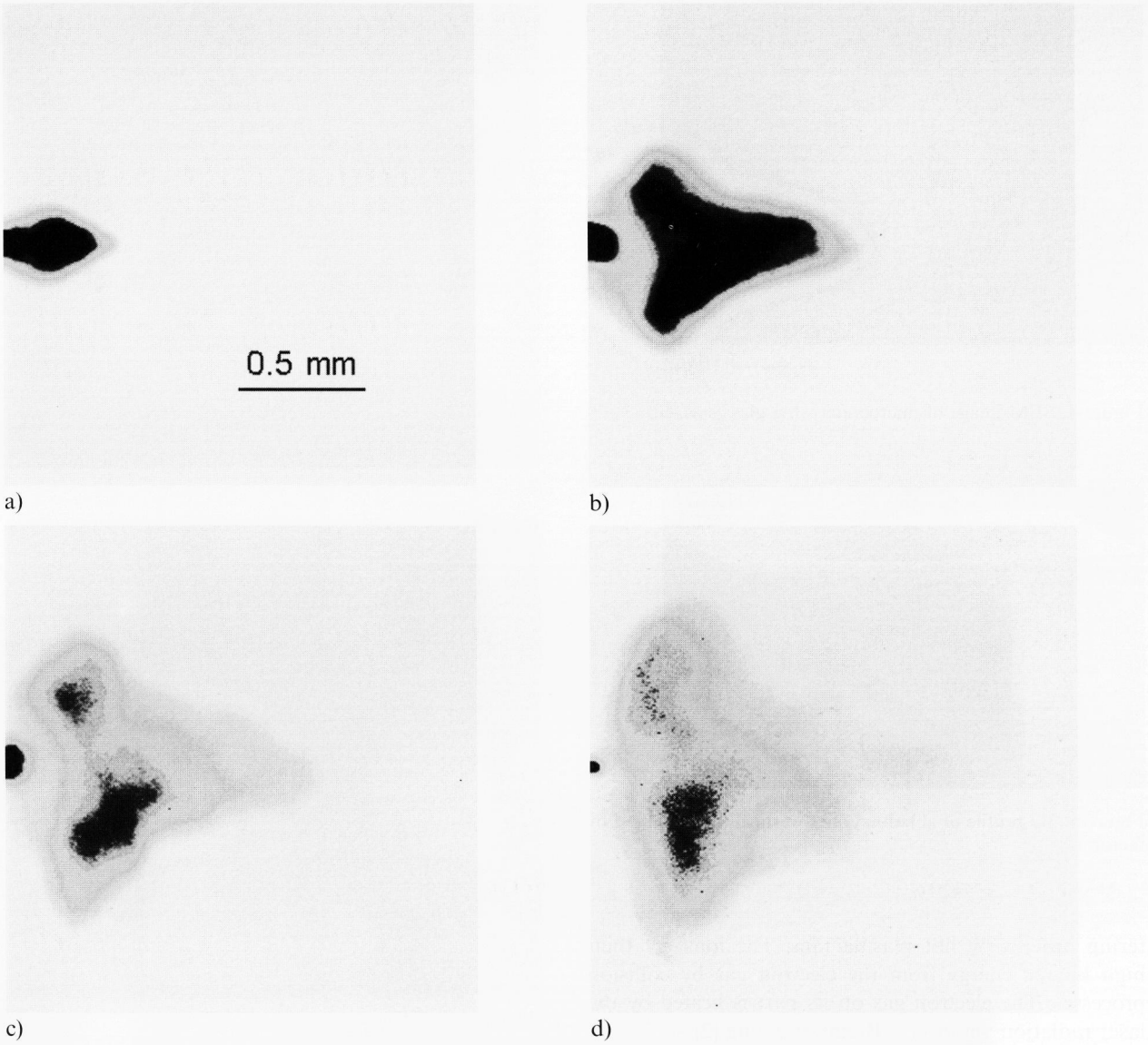
Thus k can be expressed as:

$$k = \frac{1}{4} \cdot w_0 \cdot \theta \cdot \frac{\pi}{\lambda} . \tag{4}$$

A typical value for TEM_{00} solid state lasers is $k = 1.5$.

Table 1. Laser type comparison

laser type	pulse duration	pulse energy	pulse power	repetition rate	technological suitability
q-switched, flash-lamp pumped	10 ns	100 mJ	10^8 W	10 Hz	repetition rate too low, problematic triggering because of thermal lens
q-switched, cw lamp pumped, mode-locked	300 ns/ 60 ps	10 mJ/ 120 µJ	$2 \cdot 10^6$ W	500 Hz	Nd-YLF crystal necessary because of thermal lens
q-switched, quasi-cw diode-pumped	10 ns	10 mJ	10^6 W	500 Hz (2 kHz)	problematic triggering because of thermal lens



Figures 3a to d. Sequence of four high-speed photos with exposure time of 100 ns; delay time in ns a) 0, b) 100, c) 200, d) 300.

If the laser beam is focused, the divergence angle is related to the focal length f by:

$$\theta = d/f \tag{5}$$

where d is the beam diameter at the focusing optic. Therefore, the focal spot diameter w_{0f} can be estimated by:

$$w_{0f} = 4 \cdot k \cdot \frac{f}{d} \cdot \frac{\lambda}{\pi}. \tag{6}$$

In the case of focusing an Nd-YAG laser (λ = 1.06 µm, k = 1.5, d = 10 mm) with a focal length of 100 mm, the theoretical focus diameter is 20 µm. Because of the strong rise of aperture aberration with the aperture angle, the practical value is about 30 µm and focusing with higher d/f ratio does not result in smaller focus diameter. Thus a typical focus area of $5 \cdot 10^{-6}$ cm^2 requires a pulse power of >0.5 MW to achieve power densities above 10^{11} cm^2. The most important single-stage TEM_{00}-mode laser types which fulfil this condition are listed in table 1.

4. Microplasma laser sputtering

A new field of application could be developed from using a special, laser-induced sputtering process. This sputtering regime can be realized by focusing of power densities in the range of 10^{11} W/cm^2 on or near to the target surface. Shortly after onset of the pulse the laser-induced plasma has such high electron density that the target is nearly completely shielded from the laser radiation. Therefore, the target ablation can only be a sput-

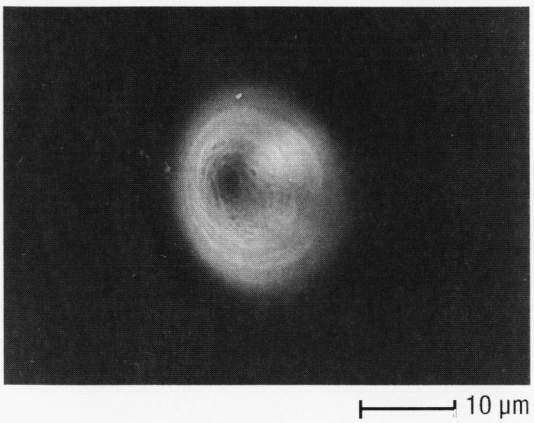


Figure 4. SEM image of microcrater on a glass surface.

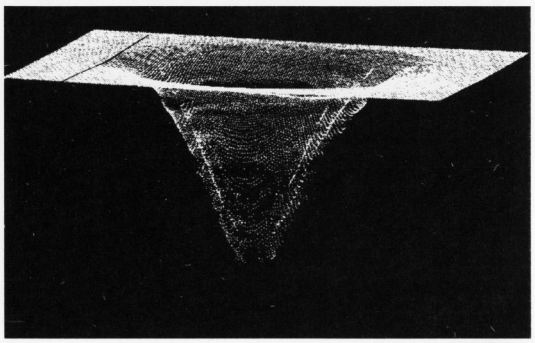
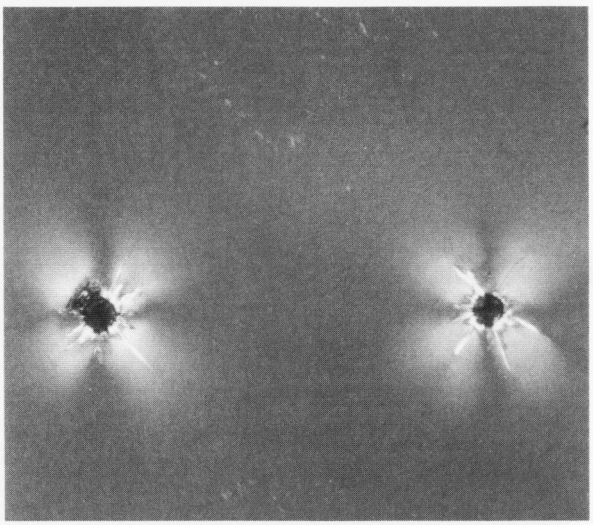
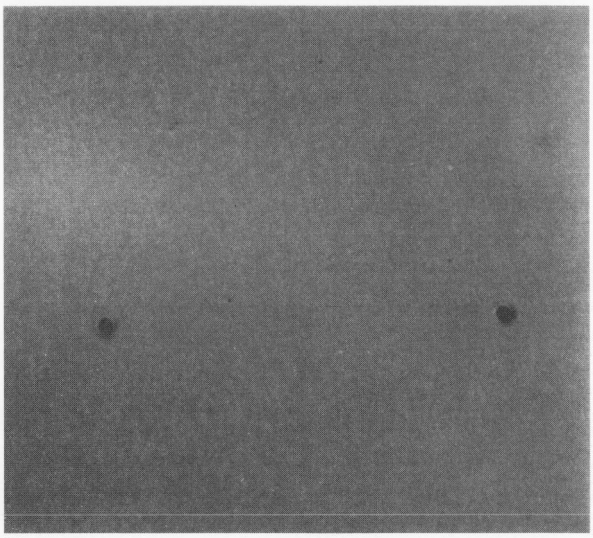


Figure 5. 3D profile of ablation crater, vertical axis enlarged by factor 10.





Figures 6a and b. Transmission microscopy images of microcraters (crossed polarization filters), point distance 0.5 mm; a) microcraters showing stress birefringence, b) microcraters without stress birefringence, produced by microlaser plasma sputtering.

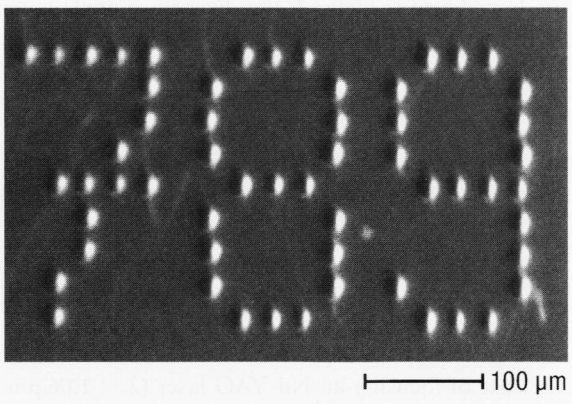


Figure 7. Micromarking by laser plasma sputtering on float glass.

tering process by hot plasma ions. The ions get their high kinetic energy from the electron gas by collision processes. The electron gas on its part is heated by the laser radiation via inverse Bremsstrahlung [2].

The formation of the laser-induced plasma was also investigated, resolved in space and time, by the special high-speed framing microscope [4 and 5]. Figures 3a to d show a sequence of four frames recording the development of one and the same laser-induced plasma for 400 ns in the case of focusing the laser at the target surface. The rather long plasma plume indicates that after the dielectric breakdown at the target surface an additional breakdown in the air is induced by the emitted plasma particles. This air breakdown results in the perfect shielding of the target from the laser radiation.

The plasma sputtering regime has two important advantages. First, the ablation area is limited to a diameter of about 20 µm (figure 4). From the lack of details one might suspect that the SEM was not correctly focused, but really the crater had such a smooth surface that there was no detail. The depth of the ablation crater determined by interference microscopy was a few micrometers (figure 5).

Second, both the surface of the crater and the surrounding surface are absolutely free of damage. There are no cracks and there is no stress detectable by optical means, which is evident from comparison of figures 6a

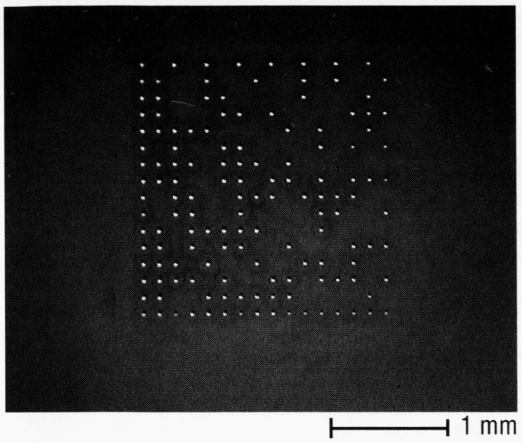


Figure 8. Micromarking of snow flake code on float glass.

and b. Both pictures were taken under the same optical conditions in a transmission microscope with crossed polarization filters. In the presence of stress, the polarization is changed, and hence the light intensity distribution forms a pattern related to the inhomogeneous stress field.

Microplasma laser sputtering could be applied in pixel-based micromarking of glass surfaces, preparing of special scattering surfaces, and nonslip finishing of glass flooring. Figure 7 shows a micromarking with a point distance of about 25 µm, and figure 8 shows a snow flake code, both on float glass. The point distance of 25 µm is the equivalent to a printer resolution of 1000 dpi. Repetition rates up to 500 Hz and higher guarantee efficient production due to short processing time.

5. Summary

Making use of nonlinear effects allows transparent media such as glass to be processed with solid state lasers. This technology requires pulse power densities in the range of 10^{10} to 10^{12} W/cm^2 connected with high repetition rates. Microplasma laser sputtering is particularly suitable for marking of glass surfaces without any damage.

6. References

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