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Technical Communication

Drilling of Through Holes in Sapphire Using Femto-second Laser Pulses

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We have studied a bottom-up ablation drilling with infrared femtosecond laser pulses. To avoid dust deposition inside the hole, we have investigated the role of focusing and scanning parameters, during the bottom-up ablation. The numerical aperture and pulse-to-pulse overlap were considered to determine an optimal ablation regime for each layer. Using these focusing conditions, a multiparametric study of laser fluence and vertical translation of focal spot was performed to determine conditions for efficient in-process dust removal. Drilling sapphire at these optimal parameters produces crack-free, chip-free, and low-tapered (< 3°) holes. We demonstrated that these parameters can be used for scaling the process for repetition rates of 1MHz and higher.

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1. Introduction

Processing of glass and a wide range of other brittle materials with a laser becomes more and more common. Laser-based processing techniques cover applications at all spatial scales: from cutting thick large panels with filamentation technique to drilling high aspect microchannels less than 1µm in diameter [1-4]. At mesoscales, defined by the size of the object larger than a few microns but smaller than a few millimeters, the ablation techniques are a reliable and easy solution for material processing.

A traditional top-down ablation technique unavoidable leaves a taper of around 8-10°, therefore, it is only suitable for micro-cutting of thin glass [5]. When drilling a high aspect ratio holes in thick glass substrates, a bottom-up ablation technique is preferred, since it produces the holes with almost zero taper [6]. In this process, the ablation starts from the rear surface of sample and then the focal spot is progressively translated to the upper layers. Fine and accurate processing is possible because the beam pathway is not distorted by such factors as shadow effects, and plasma shielding that occur during the process [6-8].

The use of picosecond (ps) and sub-ps laser sources enables higher ablation efficiencies even for transparent materials and high accuracy of produced microstructures [9]. Although the achieved quality meets industrial demands, processing speed could be improved. Therefore, the use of high repetition rate laser systems is necessary to improve the throughput of the process. However, the employment of repetition rates exceeding approximately 200 kHz in glasses involves some difficulties, because of a high risk of microcracks and chip formation caused by heat accumulation effects.

Moreover, in contrast to the regime of nanosecond ablation, regime of sub-ps ablation is associated with the ejection of molten droplets and other small hot particles [9-11]. Deposition of this debris on the hole sidewalls not only increases the taper angle but also amplifies heat accumulation effects. Indeed, these ablation products keep absorbed energy in the interaction volume, which instead should be evacuated. While these particles are deposited on the sidewall, they redistribute their energy to the surrounding material as excessive heat. Moreover, such recast layers continue to absorb laser energy afterwards. This leads to even higher local temperatures, higher thermal stresses, and increased risks of cracks formation. These effects become critical at high repetition rates, when time between two consecutive pulses is not long enough for heat dissipation. Air flow or liquid assisted laser ablation significantly reduces dust deposition, improves heat dissipation and leads to fine processing of sapphire and other glasses [12-14].

The purpose of this work is to investigate the role of controlling focusing and scanning parameters, aimed at avoiding dust deposition during bottom-up ablation of sapphire. By performing multiparametric searches of focusing and scanning parameters we seek to find a laser regime of in-process dust evacuation while keeping high laser ablation efficiency. We demonstrate such drilling in sapphire using the bottom-up ablation technique at laser repetition rates up to 1.5 MHz.

2. Experimental setup.

The experimental setup is schematically described in the Fig 1a. Femtosecond pulses (Satsuma by Amplitude Systemes, 1030nm, <500fs, up to 10µJ at 2MHz pulse repetition rate) were focused with a f-theta lens of 100 mm focal distance, while the beam was translated using a galvanometer scanner (LS-Scan by Lasea). Polished sapphire samples (c-cut) were mounted on motorized stages for translation along the z direction. The beam diameter was adjustable using a monolithic afocal beam expanders (Asphericon) with fixed values of 2x, 3x, 4x beam magnification. Therefore, focusing with variable numerical apertures (NA) is possible. Linear laser polarization was used in all experiments.

For efficient ablation of dielectrics, a pulse-to-pulse overlap higher than 90% is typically required. At such overlaps, the incubation effects are very important. Character of laser-matter interaction changes compared with the lower overlaps and the ablation is accompanied by a violent material expulsion mechanism. The material removal rate increases by an order of magnitude [9, 15]. To fulfill this requirement, the marking speed should be of the order of 2-3m/s at 1MHz pulse repetition rate for 20-30µm focal spot diameter, typically used in the experiments. Such linear displacement speed is close to the limits of our galvo scanner to perform movement along required trajectory.

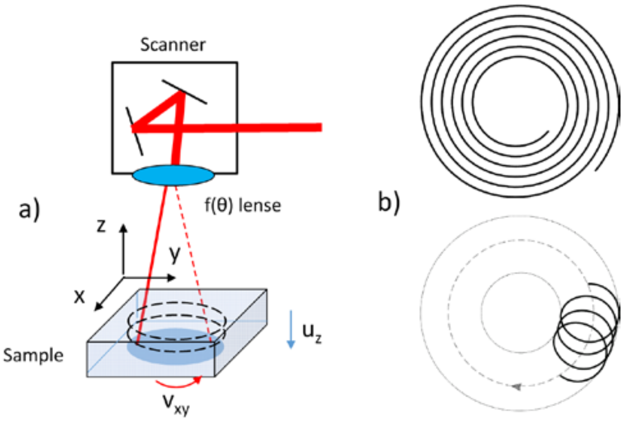

Fig. 1 a) Schema of experimental setup for the bottom-up drilling. b) Patterns for individual layer ablation: spiral (top) and "wobble" (bottom)

We have considered two patterns for marking of individual layers: spiral (Fig. 1b, on the top) and "wobble", which is beam translation along the main laser trajectory with its circular modulation at a specific frequency and amplitude (Fig. 1b, on the bottom). In both cases the central part was not processed for time saving. The spiral pattern is generally preferred for the holes ~1mm in diameter. It leads to a better dynamic and more uniform energy deposition because of better control of pulses overlap along the main laser trajectory. On the contrary, when holes of 50-100µm are required, the "wobble" may be an alternative. The reason is the following. Since, the scanner interpolates the initial circular trajectory as a sequence of the linear movements, the resulting shape, in fact, is a polygon. Deviation from the circle is more important for the small radius of curvatures. Therefore, the "wobble" is preferred to keep the circular shape in these cases.

3. Experimental protocol

Most of the studies were performed at a laser repetition rate of 500 kHz, which is below the heat accumulation regime for sapphire and allows to test small overlaps while the scanner still operates correctly. First, focusing conditions should be set, which result in the optimal laser fluence in the focal spot. As soon as focusing conditions are established, the pattern and marking speed can be adjusted, which altogether determine conditions for individual layer ablation. Finally, vertical translation of the focal spot was applied to perform an upwards helical movement. At this stage, vertical translation speed and fluence optimization were performed to determine the optimal conditions for in-process dust removal.

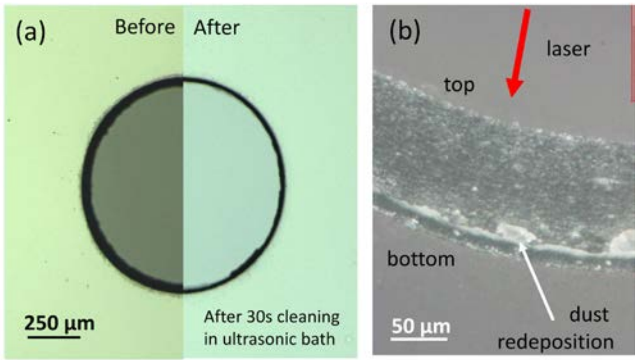

Fig. 2 a) Microscopy images of processed hole before and after cleaning in the ultrasonic bath. Dark regions are microscope artifacts due to dust redeposition and hole taper. b) Sideview of the processed hole shows that the dust is redeposited mainly at the rear side of the hole.

After the samples were cleaned (detailed procedure is explained below) the quality was evaluated. We were paying attention to the presence of dust inside the hole and on the hole taper angle $\theta=(d_{ext}-d_{int})/2h$, which is the half of a ratio of the difference between external and internal diameters of the processed hole to the sample thickness. We have processed the sapphire at different fluences and vertical feed rates while keeping the focusing and scanning parameters. That allowed us to determine the range of conditions whereby successful drilling was achieved. Using this data, we studied the scalability of the process at higher repetition rates.

3.1 Focusing and scanning conditions at 500 kHz.

To adapt our setup for reliable drilling, beam diameter and focal lens had to be correctly set. Indeed, if NA of the focusing configuration is too small, nonlinear effects may initiate the filamentation effect which may prevents focusing to a required spot size and limiting the maximal fluence [16]. On the other hand, if NA is too high, it appears that dust evacuation is difficult when drilling the deep holes. Thus, only a certain hole depth can be reached before the moment when redeposited dust completely prevents further drilling. We found that using NA between 0.08 and 0.15 is optimal since we always can find a compromise between high fluence required for efficient ablation and high efficiency of dust evacuation. We suppose that such NA can be beneficial for drilling because of an extended Rayleigh length Z_R of the focused beam. For NA=0.1 Z_R equals to 180 µm, which favors efficient dust evacuation by secondary ablation of recast layer.

Numerical aperture NA=0.08 was arbitrarily chosen for a majority of tests, which corresponds to 8.2 mm beam diameter (at level $1/e^2$) focused with 100mm f-theta lens. At these conditions, a focal spot diameter was measured to be equal to 26µm [17]. For drilling 1mm diameter holes, the spiral patterns included 30 loops were used. The internal diameter of a spiral is 0.5 mm. That gives as a pitch of 8µm between two consecutives loops of spiral. No significant change in single layer ablation is observed for beam displacement speed in the range between 250mm/s and 1m/s. Lower and higher speed results in a generation of cracks. It means, that at high speed when overlap was kept <92%, ablation was not efficient. Otherwise, when overlap was >98% heat accumulation could be too important to generate the cracks. While overlap was chosen between 92% and 98%, the parameters for efficient drilling can be always found. Fig 2a. shows typical quality after drilling in close to the optimal regime at 500 kHz. Fluence of 2.5 J/cm^2 and vertical progress speed of 40µm/s, was used. Pulse duration is t_p=500 fs. Beam translation speed is 500mm/s giving the overlap of 96%. Linear polarization of incident light was used, however no asymmetries in processed holes was observed.

Dust, deposited near the rear surface was found omnipresent for each irradiation conditions. On the transmission microscopy images, it appears as dark zones inside the hole. To remove it, post-processing of samples was performed by cleaning them in ultrasonic bath in distilled water for 30-60s. The quality of the hole before and after cleaning in ultrasonic bath (30 s) is demonstrated in Fig. 2a. It demonstrates that this procedure allows to eliminate majority of dust. Some residues can be still visible near the rear side of the sample (see fig 2b). On the microscopy images, they appear like more thick and dark ark in the left right corner of the hole. However, the hole conicity was not removed completely. Another reason for it, is the taper arising during regular top/down ablation. Indeed, while we are approaching the top of the sample, intensity at the front surface constantly increases, thus ablation starts after a certain threshold depth. Instead of having pure bottom-up ablation, at certain parameters we may have a hybrid bottom-up/top-down process with a taper near the top surface [8].

3.2 Vertical translation at 500 kHz

Successful drilling is achieved already at the fluence 1.9 J/cm^2. This value is just after the ablation threshold for sapphire (1.6 J/cm^2). Processing at 5µm/s vertical translation was only possible, producing the holes with the taper angle of 14°. Two factors contribute to such conicity: the dust recast layer, which is difficult to remove near the rear surface of the hole, and significant conicity of the hole itself. With an increase of fluence there is less residual dust observed, taper angle decreases down to 3° and resulting processing speed increases.

We performed the study up to of 3.1 J/cm^2. Above this fluence value no improvement was achieved neither for z translation speed, nor for improvement of hole conicity. Indeed, the maximal vertical feed rate at which the hole was successfully drilled was limited by 70µm/s for every fluence above 3.1 J/cm^2 at 500kHz and the given spiral pattern. Regarding the conicity, as shown on Fig. 3a, it reaches its minimum value of 3° already at 2.5-2.8 J/cm^2 and cannot be improved anymore using present focusing conditions. It appears that for every fluence there is an optimal vertical feed rate. For example, at the fluence of

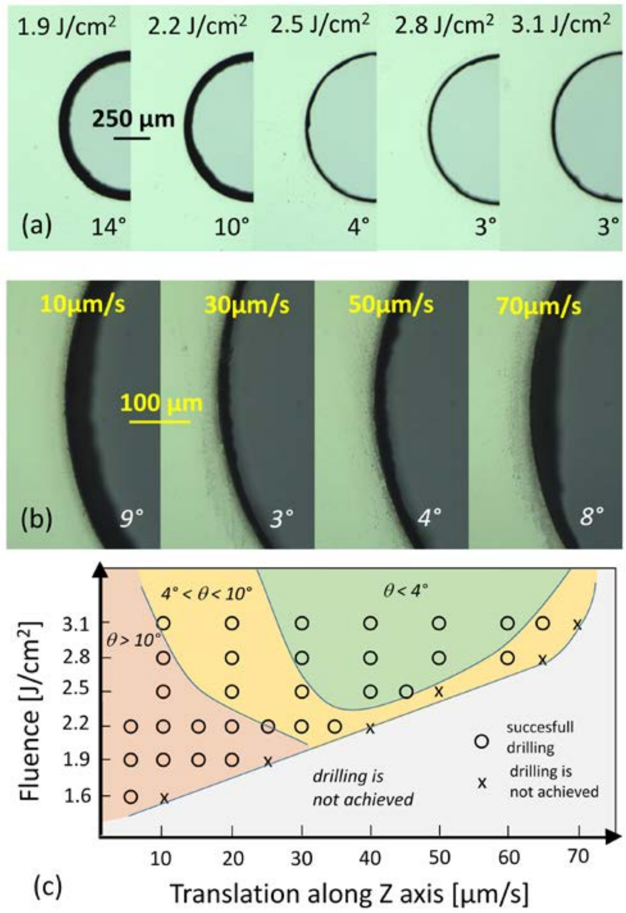

Fig. 3 Drilling of sapphire at 500kHz, NA=0.08, t_p=500fs. a) Processing at different laser fluencies. Image is composed from the best quality holes at corresponding fluence. Minimal conicity speed is indicated for each fluence value. b) Processing at 3.1 J/cm^2 and different vertical translation speed. Taper angle is indicated for each value of feed rate. c) Processed windows for drilling capability and taper angles at different laser fluences and vertical feed rates. The area of optimal parameters is indicated in green where processing of low conicity holes is systematically achieved.

3.1 J/cm^2, as shown in Fig. 3b, processing at slow vertical translation leaves more dust in the hole which is hard to remove. Meanwhile, when the speed is too high, the laser dose is not enough to produce a clear hole. This defines the optimal range of 30-60µm/s where the taper angle of 3° is systematically achieved. The process window leading to successful bottom-up drilling is resumed in Fig. 3c.

3.3. Results at 1 MHz

To process at higher repetition rate, we have used a map of optimal conditions depicted in Fig 3c. By choosing 2.8 J/cm^2, which is a lower fluence but still within the optimal conditions area, we expected to minimize any heat accumulation effects. At 1MHz pulse duration decreases down to 300fs. A shorter pulse duration should affect ionization thresholds; however, we were not able to detect significant differences in drilling quality. Therefore, tests were performed at this pulse duration. To keep the same overlap scanning speed were doubled to 1 m/s, allowing us to drill holes at twice faster vertical displacement speed. Vertical

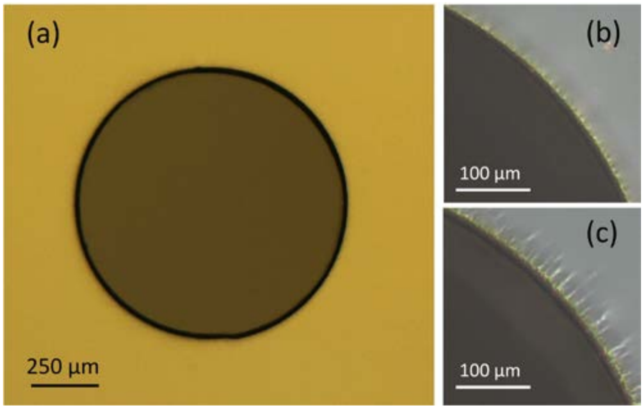

Fig. 4. a) Optical transmission microscopy image of drilling at 1MHz, 2.8 J/cm^2, NA=0.09, t_p=300fs, scanning speed 1 m/s, vertical translation speed 100 µm/s. Residual stresses and internal defects may be revealed in cross-polarized light illumination in the case of b) optimal exposure c) and when overexposure of incident surface takes place.

displacement up to 120 µm/s is possible, however optimal parameters with a taper angle of 3° were achieved at 100µm/s. This enables us to drill 1 mm diameter hole in 300µm sapphire sample in a time less than 3s.

As shown in Fig. 4, the hole entrance surface is not damaged, there is no chipping, and no cracks. The cleaning procedure leaves no dust deposited near the exit surface. In the same way, processing conditions were determined for repetition rates up to 1.5 MHz, where no significant thermal effects were detected for sapphire. Close inspection of hole quality at higher repetition rates was performed using cross-polarization microscopy. This technique allows to visualize internal defects and laser modifications appearing as stressed regions around the produced modifications.

In Fig. 4b no residual stresses and no damage in surrounding bulk material are observed in optimal condition. On the other hand, it indicates that the accurate control of deposited energy dose is required. When the pulse energy is too high, or laser exposition time is longer than required, volume modifications were induced leaving residual stresses (see Fig 4c). These internal modifications can extend towards back surface leaving backside damage rings, characteristic to top-down ablation process. These defects appear when incident radiation refracts on the conical entrance surface. Laser radiation can penetrate in the vicinity of the hole leaving volume modifications and damaging the rear side of the sample [8]. Therefore, zero-taper drilling provides also several benefits since there is no esthetical artifacts around hole and no internal modification. This indicates on a higher overall quality of process.

No anisotropic behavior was detected in cross polarizers microscopy observations. Despite the linear polarization was chosen for the experiments, which were performed in the crystalline material, a distribution of intra-volume defects (while they are present) is circularly symmetric. Therefore, the produced damage is defined by the symmetry of the hole and is not affected by laser beam polarization. Furthermore, we did not observe that the intra-volume damage defects are dependent upon the crystalline axis of sapphire.

Conclusion

We performed a parametric study of laser and scanning parameters which lead to efficient in-process dust removal during the bottom-up ablation drilling using femtosecond laser pulses. The most efficient dust removal occurs when focusing with the numerical aperture in the range between 0.08 and 0.15. We attribute it to the long Rayleigh range of focused beam; deposited dust can be removed by consecutive laser passes. Performing a parametric study of laser fluencies and speed of vertical translation of focal spot, optimal parameters can be defined leading to the drilling of high quality holes with no chipping, microcracks, internal defects, and low taper angle (<3°). Using these data, conditions for processing at higher repetition rate up to 1.5 MHz can be defined resulting in multiple gain of throughput.

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