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Advancing femtosecond laser percussion drilling for high-aspect-ratio holes in glass and silicon carbide using repetitive single-pulses

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Abstract

The demand for micrometric through-holes in glass and silicon carbide (SiC) is growing, particularly in advanced packaging and power electronics. While selective laser etching (SLE) remains the dominant method for through-glass vias (TGVs), environmental concerns and process complexity highlight the need for alternatives. One option is percussion drilling, but it faces challenges such as drilling saturation due to the conical shape of the hole, microcracks, and stress. Recently, GHz burst processing has attempted to address these issues, but some fundamental limitations remained. In this study, we showcase the unexplored potential of repetitive single-pulse femtosecond laser drilling. Using optimized focusing conditions and a femtosecond fiber laser with >200 µJ pulse energy and 270 fs duration, we achieved full penetration of up to 1 mm - thick glass and fast SiC drilling.

Keywords: TGV, drilling, femtosecond laser, percussion drilling, deep drilling, glass, silicon carbide

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1. **Introduction**

Laser micro-machining, particularly with femtosecond lasers, has revolutionized precision material processing across various industries, from consumer electronics to biomedical devices (Niu et al., 2024; Tian et al., 2022). Its ability to deliver ultra-short pulses of light minimizes heat transfer to the material, enabling "cold ablation" and thus mitigating common thermal side effects like cracking, melting, and the formation of heat-affected zones (HAZ) (Feng et al., 2024). This inherent precision makes femtosecond lasers suitable for processing brittle and transparent materials that are challenging for conventional methods.

The demand for high-quality micro-features, such as through-vias and blind holes in diverse materials like glasses (e.g., BK7, Eagle XG) and semiconductors (e.g., silicon carbide), is rapidly growing. These materials are critical components in advanced optical systems (Niu et al., 2024), microelectromechanical systems (MEMS) (Linden et al., 2023), and high-power electronics (Yu et al., 2022), necessitating highly precise and efficient processing techniques. While femtosecond laser ablation offers unparalleled precision, optimizing the process for different material properties and desired geometries remains a significant area of research. Key challenges include achieving high aspect ratios, minimizing taper angles, avoiding material redeposition, and preventing micro-cracks, especially in inherently brittle materials like silicon carbide.

Previous research has explored various aspects of femtosecond laser-material interaction, including the influence of pulse energy, repetition rate, and pulse duration on drilling mechanisms (Stępak et al., 2025). However, specific material responses, particularly concerning phenomena like internal material redeposition in glasses or crack formation in brittle semiconductors under different pulse delivery strategies (e.g., single-pulse vs. burst mode), still require deeper investigation. Understanding these intricate interactions is crucial for developing robust and scalable industrial applications.

This paper presents a comprehensive experimental study on femtosecond laser micro-drilling of BK7 glass, Eagle XG glass, and silicon carbide. We specifically investigate the impact of critical laser parameters, including pulse repetition rate, pulse

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duration, pulse energy, and the number of delivered pulses, on hole geometry, quality, and processing efficiency. Particular attention is given to optimizing drilling conditions to overcome material-specific challenges, such as minimizing taper in Eagle XG glass and preventing cracking in silicon carbide.

2. **Experimental**

The experimental setup utilized a Fluence Jasper X1 femtosecond laser, characterized by a fundamental wavelength of 1030 nm and a tunable pulse duration ranging from <270 fs to 20 ps. The nominal pulse repetition rate was set at 150 kHz, delivering a single pulse energy of 200 µJ. The laser system offered operational flexibility, allowing for both single-pulse mode and burst mode, with the latter accommodating up to 12 pulses per burst and featuring a 50 ns intra-burst delay. Furthermore, a High Energy Burst mode was available, which reduced the maximum repetition rate to 100 kHz while increasing the burst energy to 300 µJ. The laser beam was precisely directed to the workpiece via a galvoscanner (Scanlab excelliSCAN 14) integrated with a telecentric objective. The objective's position was controlled using a high-precision linear translation stage to ensure accurate focusing.

All drilling results presented in this study were obtained using the percussion drilling method. During this process, the laser beam remained stationary until a predetermined number of pulses (NoP) had been delivered to the target. This research specifically investigated the influence of key laser parameters, including pulse energy, repetition rate, pulse duration, and the total number of delivered pulses, on the drilling outcomes. For the experiments, two types of glasses were employed: 1.1 mm thick Schott BK7 and 0.5 mm thick Corning Eagle XG. Additionally, 120 µm thick silicon carbide samples with a 4H lattice orientation were utilized. The in-situ drilling process within the material was continuously monitored by a Bassler CMOS camera, positioned perpendicularly to the optical axis of the laser beam, allowing for real-time observation.

3. **Results**

3.1. *BK7 glass*

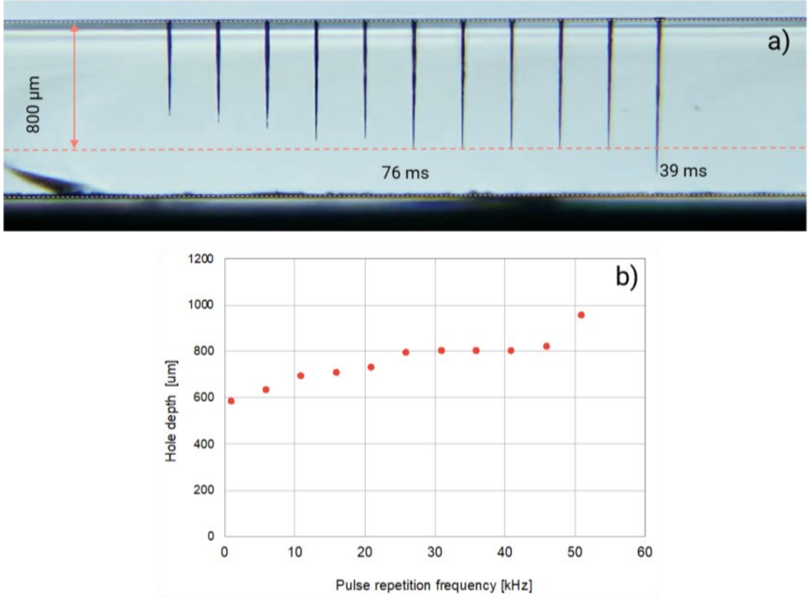

Fig 1: The view of holes drilled in BK7 glass, sideview (a); the dependency of pulse repetition rate on hole depth (b).

The experimental investigation into blind hole drilling in BK7 glass revealed a significant dependence of hole depth on the pulse repetition rate when operating in single-pulse mode. As illustrated in Fig. 1, an increase in repetition rate directly correlates with greater achievable depth. Optimal drilling speed and maximum depth, free from cracks and a noticeable heat-affected zone, were observed at 52 kHz. Exceeding this repetition rate led to an increased tendency for material fracture. Furthermore, within the BK7 glass, the drilling depth exhibited a linear increase up to 600 µm with the delivery of up to 1400 pulses to a single spot. Interestingly, the hole width at specific depths unexpectedly narrowed with a higher number of delivered pulses, a phenomenon likely attributed to the redeposition of molten glass within the drilled structure. Fig. 2 distinctly shows that holes formed with fewer pulses are considerably wider at comparable depths compared to deeper holes. Consequently, the taper angle of the holes increased from 0.1 to 1.2 degrees with a rising pulse count. Beyond the 600 µm depth, the drilling speed substantially decreased, requiring several thousand additional pulses to achieve through-hole formation. These findings were obtained using a pulse energy of 200 µJ, a repetition rate of 20 kHz, and a numerical aperture of 0.1.

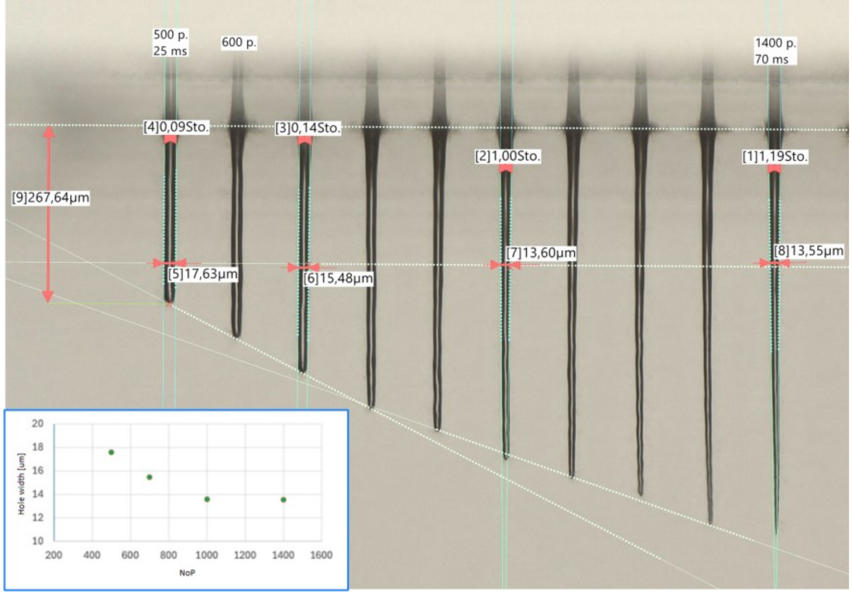

Fig. 2: Side view of holes drilled in BK7 glass with increasing number of pulses. The NoP starts from 500 and increases up to 1400 by 100. Inset: dependency of NoP to measured hole widths.

A comparative analysis of two laser pulse widths, 250 fs and 10 ps, was conducted to assess their impact on hole quality and depth (Fig. 3). Holes drilled with longer pulses (10 ps) were approximately 40% shallower and exhibited an undulating shape, indicating superior performance of shorter pulse durations for this material.

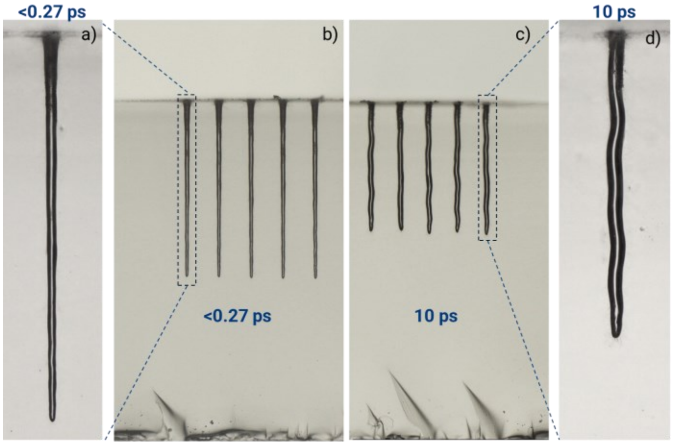

Fig. 3: Side view of hole series drilled with 270 (b) and 10 ps (c) with their closeups respectively (a,d).

3.2. *Eagle XG glass*

Percussion drilling of through holes in Eagle XG glass using ultrafast lasers presented a notable challenge, specifically the formation of a very narrow hole opening. While it was possible to enlarge the exit diameter to 5 µm, this enlargement process required an equivalent number of pulses as the initial through-hole drilling, effectively doubling the processing time and significantly reducing efficiency. Through optimization of the focus position and beam size, we successfully achieved significantly less conical holes with an impressive outlet diameter of approximately 12 µm. Fig. 3 depicts the enhanced hole shape, characterized by clean and transparent edges. The resulting holes featured an inlet diameter of around 31 µm, a reduced taper angle below 0.25 degrees, and an aspect ratio of 27:1. These improved results in Eagle XG glass were obtained with a pulse energy of 200 µJ, a repetition rate of 10 kHz, and a pulse duration of 270 fs. The total number of pulses required to drill through the material was 2000.

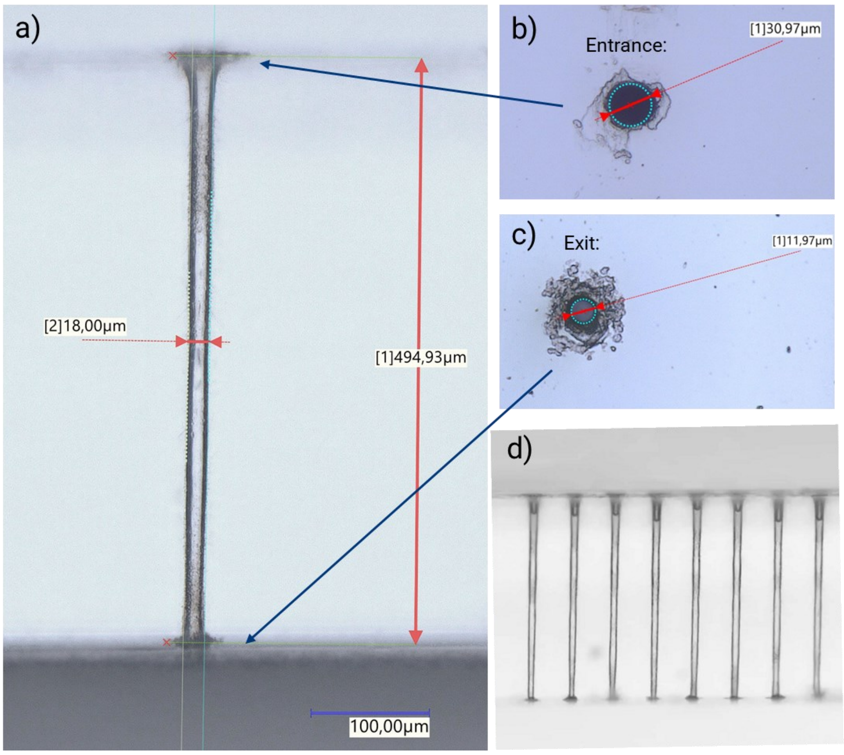

Fig. 4: Side view of through hole drilled Eagle XG (a); its entrance (b) and exit (c); series of holes drilled with the same process parameters (d).

3.3. *Silicon carbide*

Percussion drilling of silicon carbide (SiC) proved challenging due to its inherent brittleness. When operating in single-pulse mode, the material consistently developed cracks, both within the bulk volume and at the hole exit. Attempts to mitigate this issue by reducing pulse energy, repetition rate, or wavelength did not yield improved results. However, the implementation of burst mode offered a solution to the cracking problem. As illustrated in Fig. 5, utilizing twelve pulses per burst resulted in the formation of clean, crack-free holes with a diameter of 21 µm. This approach allowed for the use of burst energies up to 300 µJ for through-hole drilling. It was observed that for this specific material, the number of delivered bursts was critical in preventing chipping at the hole exit, a phenomenon that occurred even at lower burst energies.

Drilling efficiency in silicon carbide was found to be strongly correlated with pulse duration (Fig 5). For a given number of pulses, the deepest holes were consistently achieved at a pulse duration of 270 fs, maintaining a comparable quality to holes drilled with other pulse widths.

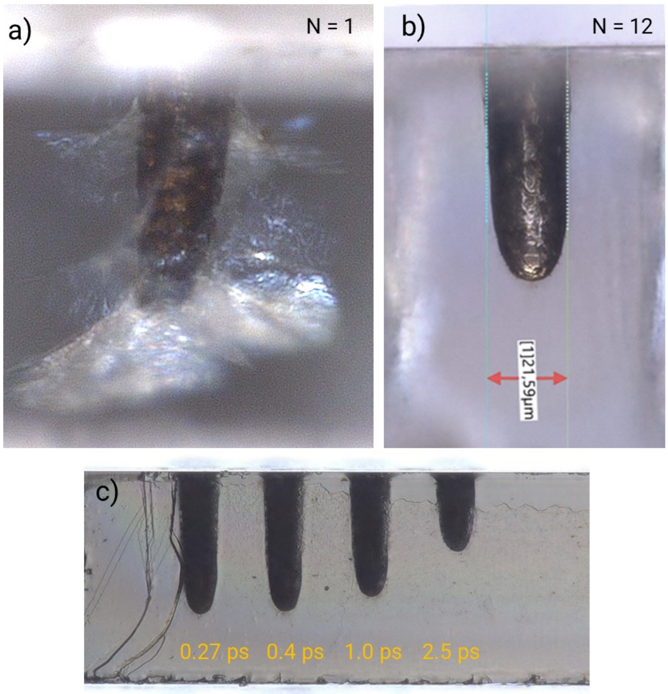

Fig. 5: Side view of hole drilled in SiC with single-pulse (a) and burst (b) mode; series of holes with increasing pulse duration (c).

Ultimately, the 120 µm thick silicon carbide samples used in this research could be drilled through effectively at a repetition rate of 100 kHz with a burst energy of 300 µJ without inducing material fracture. With an optimal number of 160 bursts, the processing time per hole was remarkably low, measuring less than 2 ms. This demonstrates the potential to fully utilize the 30 W power of the Jasper X1 laser operating in its High Energy Burst mode for efficient SiC micro-drilling. The optimized optical setup employed in this experiment enabled the creation of through holes with a 23 µm entrance diameter and an 11 µm exit diameter. A side view of a representative hole is presented in Fig. 6.

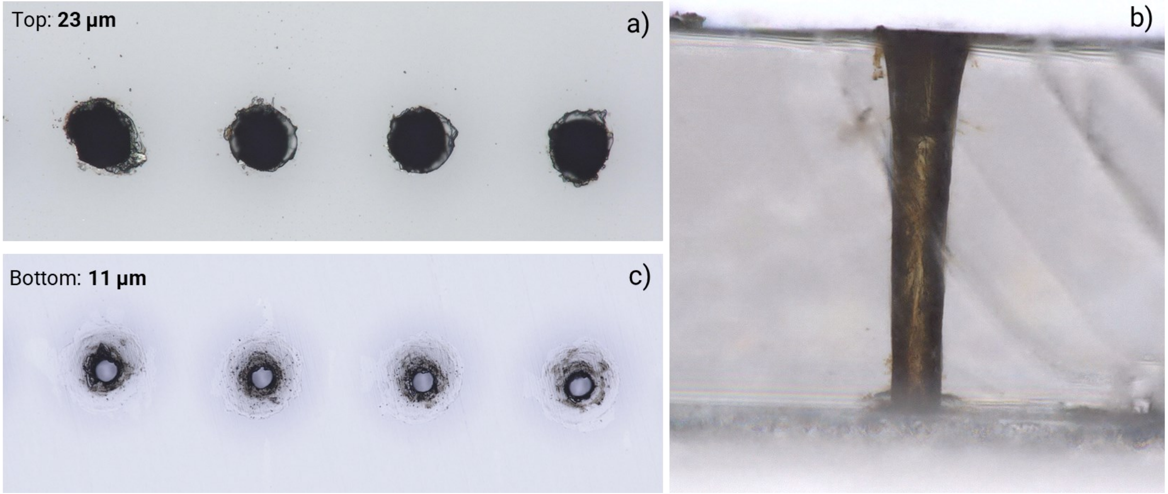

Fig. 6: Holes in SiC drilled with 12 pulses in a burst at 100 kHz pulse repetition rate and 30 W average power: entrance (a); side view (b); exit (c).

4. **Conclusions**

This study successfully demonstrated the capabilities of femtosecond laser micro-drilling for various transparent and brittle materials, specifically BK7 glass, Eagle XG glass, and silicon carbide. Our findings highlight optimal processing strategies that balance quality and throughput for each material.
For both types of glass, the most favorable results, in terms of drilling quality and efficiency, were consistently achieved using a single-pulse mode with a pulse duration below 270 fs. Conversely, for silicon carbide, the burst mode operating with 12 pulses per burst at <270 fs proved to be a transformative approach, significantly enhancing drilling outcomes.
In BK7 glass, we demonstrated rapid and linear blind hole drilling up to 600 µm depth, yielding holes with notably clean and smooth walls at a pulse duration of 270 fs. An intriguing phenomenon of glass redeposition onto previously drilled areas was observed. This effect led to an unexpected narrowing of the hole's waist and a corresponding increase in the taper angle as more laser pulses were delivered.
Furthermore, through optimization of process parameters, we effectively overcame the challenge of producing narrow exit diameters in Eagle XG glass vias. The optimized holes are characterized by entrance and exit diameters of 31 µm and 12 µm, respectively. These holes exhibit a remarkably low taper angle of below 0.25 degrees and the aspect ratio of 27:1.
Finally, while single-pulse drilling of silicon carbide consistently resulted in significant material defects, primarily in the form of cracks, the strategic application of burst mode enabled the creation of high-quality vias. This method allows for the utilization of the laser's full power, making it possible to drill hundreds of vias per second. Such high throughput, combined with superior quality, positions this process as highly attractive for future applications in power electronics.

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