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Glass percussion drilling with GHz-burst femtosecond lasers at 515 nm and arbitrary burst shapes

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Abstract

The GHz-burst femtosecond laser regime has attracted growing interest for its applications in glass percussion drilling. In this work, we introduce an innovative GHz-burst femtosecond laser (800fs, burst energy >0.3mJ) operating at a green wavelength (515 nm), uniquely capable of generating arbitrary burst shapes. This advanced laser system unlocks new opportunities for optimizing ablation processes in glass percussion drilling. By combining the advantages of the green wavelength with tailored GHz burst profiles, we demonstrate that the interaction between the laser and the glass is significantly improved, resulting in faster drilling and higher-quality holes with smoother surfaces and absence of cracks. This approach lays the groundwork for advancing the understanding of GHz-burst laser processing and its transformative impact on glass drilling techniques.

Keywords: fs GHz-burst; percussion drilling; ultrafast laser processing, glass; crack-free holes

1. Introduction

Femtosecond (fs) laser micromachining with GHz-burst pulse structures has rapidly emerged as a transformative approach for precision drilling of transparent materials, combining sub-micron resolution with reduced thermal damage. Unlike conventional ultrafast lasers, which often struggle with issues like microcrack formation, redeposition, and low throughput during glass drilling (Yan et al., 2016), the GHz-burst regime enables controlled energy delivery and improved material response (Lopez et al., 2022a; Gaudfrin et al., 2022).

Several studies have demonstrated the effectiveness of burst shaping—manipulating the number, timing, and energy of sub-pulses within a burst—to optimize ablation dynamics across different glass types. In particular, recent work has shown that tailored GHz bursts significantly improve hole quality in borosilicate, fused silica, and even more challenging vitreous materials, enabling crack-free, clean-edged drilling at higher throughput levels (Lopez et al., 2023; Grossman et al., 2017). The advantages are particularly notable when processing thicker substrates or when targeting specific geometries, where stress accumulation can be a limiting factor.

In this work, we present percussion drilling results in fragile transparent substrates—including borosilicate, fused silica, and semiconducting glasses—using a new compact femtosecond laser platform operating at 515 nm with GHz intra-burst repetition rates and customizable burst shaping. This system, delivering up to 100 W of average power in its fundamental wavelength, offers real-time control over burst parameters such as total energy, duration, and sub-pulse count—crucial for adapting to diverse material properties.

Our experimental results confirm that precise burst control enables energy confinement within the focal volume, minimizes peripheral damage, and avoids microfractures even in holes with high aspect ratio. Crack-free, reproducible holes with excellent dimensional control were obtained without post-processing, demonstrating that GHz-burst fs lasers provide a versatile, scalable solution for high-precision microdrilling in various glass types. These findings underline the growing role of GHz-burst technology in industrial glass micromachining, where both quality and throughput are critical.

2. Materials and methods

2.1. Laser source

Percussion drilling experiments were carried out using the FEMTOFLASH 20 laser (Lithium Lasers, 20 W, 0,8 GHz), a highly compact and flexible source based on fs GHz-burst technology (Fig. 1). Unlike conventional systems, FEMTOFLASH natively operates in the GHz burst regime, leveraging a patented architecture built around a high-frequency, high-power solitonic mode-locking oscillator. This oscillator is followed by an AOM-based modulation system, enabling fully programmable burst shaping and a single or double-stage amplifier for the 20 and 100 W version respectively.

A key advantage of FEMTOFLASH lies in its compact integration: all control electronics are embedded within a 420×294×145 mm box (Fig. 2a), simplifying system integration in production environments. Most importantly, the platform offers full independent control over key burst parameters (Fig. 3), including:

- Burst repetition rate: unlike conventional systems based on discrete frequency multiplication/demultiplication, our approach enables continuous modulation of the burst rate, as it is obtained by sampling a train of continuous fs pulses from a high-power GHz-repetition-rate oscillator.
- number of pulses per burst: thanks to the direct sampling from the GHz oscillator, we can also generate bursts with an arbitrary number of pulses (ranging from 25 up to more than 1000), overcoming the limitations of other GHz burst-mode laser technologies.
- Intra-burst energy distribution.

Drilling was performed in percussion mode, with the beam kept stationary over the sample while varying the number of bursts, pulse energy, and focal position (Fig. 4).

The laser is available in both green (515 nm) and IR (1030 nm) wavelength. Most of the results showed in this work refers to experiments with green wavelength. However, some new results obtained with the infrared wavelength and the new, higher-power (100 W) version of the laser (FEMTOFLASH 100) are also shown.

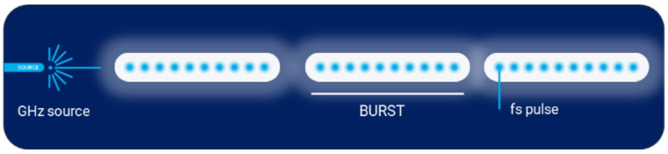

Fig. 1. GHz fs FEMTOFLASH laser technology.

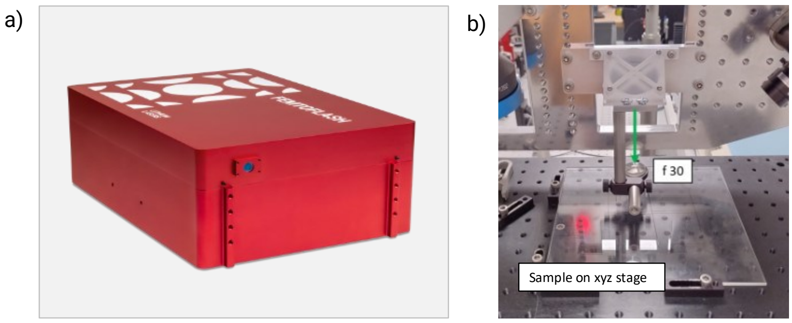

Fig. 2. (a) FEMTOFLASH laser from Lithium Lasers, (b) Setup for percussion drilling with a borosilicate sample on the xyz stage.

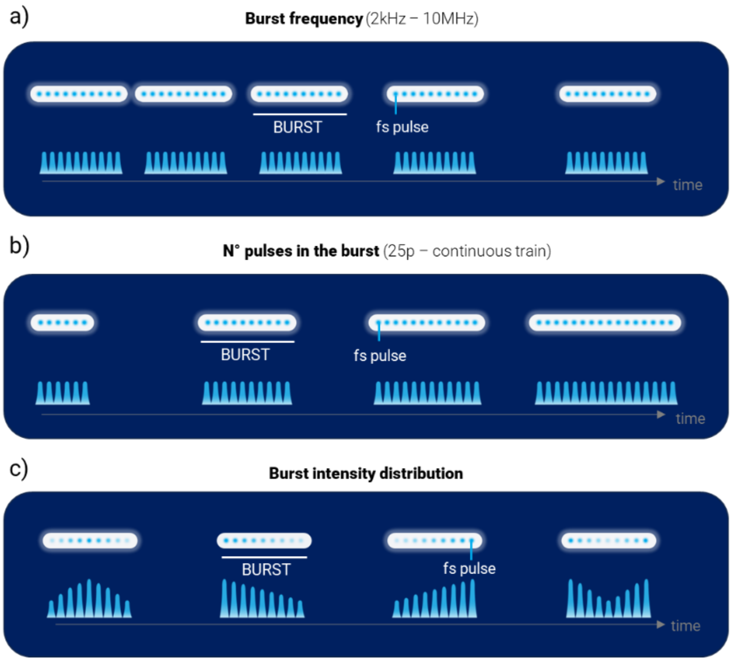

Fig. 3. Modulation of different laser parameters: (a) Burst frequency, (b) number of pulses in the burst, (c) Burst intensity distribution.

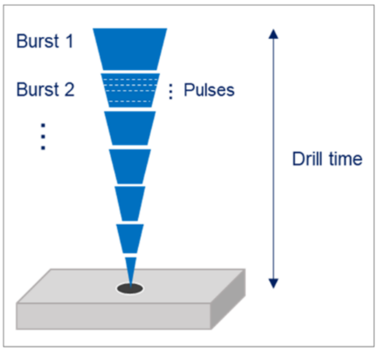

Fig. 4. Laser parameters adjusted to optimize the percussion drilling process.

2.2. Experimental setup

The laser beam was focused onto the surface of sample, placed on a XYZ motorized stage, using a set of different achromatic lenses to match with the desired spot size (Fig. 2b). Percussion drilling was carried out in ambient conditions. The machined samples were inspected by optical microscope (Nikon Eclipse LV150) both in top view and in cross-section (when it was possible).

2.3. Materials under test

Three main classes of materials were investigated to evaluate the performance of GHz-burst percussion drilling:

- Borosilicate Glass:
  - 20x20x1mm BF33 from NanoQuarz Wafer GmbH
  - 200x200x3,2mm AF32 for display applications.
- Fused Silica: 20x20x1mm samples from NanoQuarz Wafer GmbH.
- Semiconductor materials: silicon wafers (570 µm thick) and silicon carbide wafer (350um thick).

3. Results and discussion

This section presents some examples of experimental results obtained at Lithium Lasers application laboratory, using the FEMTOFLASH 20 and FEMTOFLASH 100 laser systems for percussion drilling. The tests were carried out to assess the laser's performance in response to specific industrial application requirements, with a focus on processing quality, reproducibility, and ablation efficiency for each material.

3.1. Borosilicate

We performed percussion micro-drilling tests on thick borosilicate glass displays (200x200x3,2mm) by using FEMTOFLASH 20W laser at 515nm. The main objective was to create shallow pockets about ten micrometers deep on borosilicate display substrates, with varying diameters. Using a low number of pulses per burst (100), we achieved highly reproducible holes with diameters below 10 µm (Fig. 5). When increasing the pulse count above 1000, the hole diameter also increased—for example, with 1800 pulses per burst, holes reached approximately 20 µm in diameter (Fig. 6). Although the amount of debris generated during milling increased with higher pulse numbers, the holes remained consistently crack-free and well-defined across the drilled matrices. This demonstrates excellent control over hole size and quality by adjusting burst parameters.

Additionally, we utilized FEMTOFLASH 100, operating at 1030 nm wavelength to drill both blind and through holes in 1 mm thick borosilicate samples: an example of blind holes is reported in Fig. 7. By varying the burst parameters, we were able to modulate the holes' aspect ratios while maintaining crack-free quality:

- 100kHz, 100 pulses in the burst, 1ms drill time: specific ablation rate 0.21 mm3/W/min (Fig. 7a, 7b).
- 100kHz, 50 pulses in the burst, 5ms drill time: specific ablation rate 0.19 mm3/W/min (Fig. 7c, 7d).

This confirms the scalability and robustness of our GHz femtosecond burst technology for precision micro-machining on borosilicate glass, even working with IR wavelength.

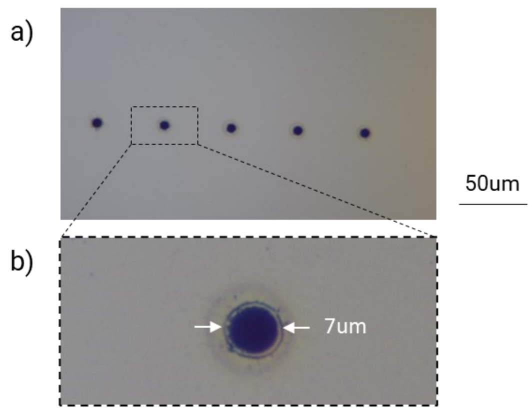

Fig. 5. (a) Hole line in thick borosilicate sample (3mm) at 75kHz, 100pulses within the burst, 10us.
(b) Higher magnification of a single hole showing a diameter under 10um, without cracks.

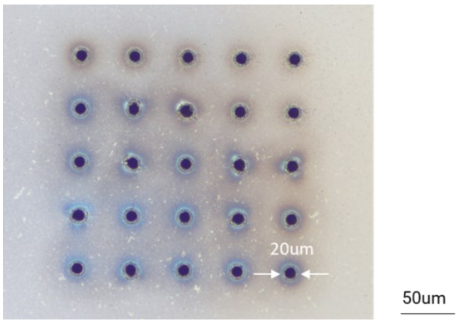

Fig. 6. Crack-free hole matrix in thick borosilicate sample (3mm) at 75kHz, 1800pulses within the burst, 10us. Increasing the number of pulses leads to an increase of the hole diameter up to 20um.

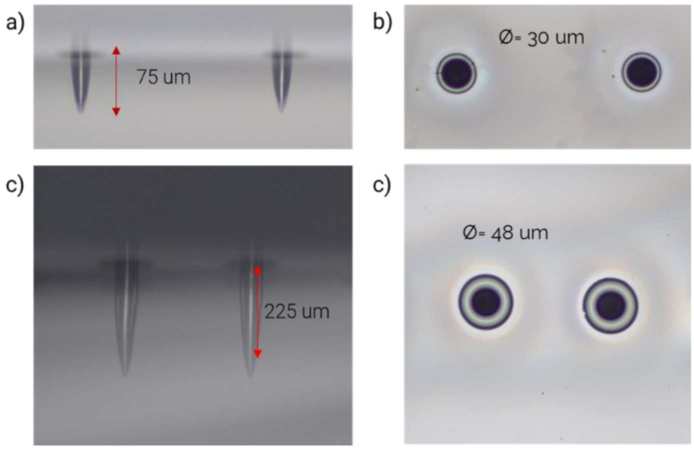

Fig. 7. Optical images of blind holes in 1mm thick BF33. (a) cross-section and (b) relative top view of holes obtained at 100kHz, 100pulses, 1ms. (c) cross-section and (d) relative top view of holes obtained at 100kHz, 50pulses, 5ms.

3.2. Fused silica

For fused silica samples, we focused on optimizing drilling depth and aspect ratio. We operated in a low number of burst regime (2-200), where the drilling process is known to be more efficient according to the literature (Balage et al, 2023). FEMTOFLASH 20W (515nm) set at 2kHz, 1000pulses (corresponding to an average power of 1,4W), crack-free holes with a diameter between 10 and 12um have been obtained. By varying the burst number between 2 and 2000 pulses, we were able to precisely control hole depth and aspect ratio, from 4 to 36, to meet application-specific requirements (Fig. 9a). Our results show that hole depth increases with the number of pulses per burst, while the ablation rate decreases due to longer drilling times. Moreover, we demonstrated that adjusting the focal spot size in the setup allows further control of process efficiency: by using a larger focal lens, we could approximately double the drilling depth increasing the specific ablation rate (Fig. 9b).

FEMTOFLASH 100 laser (1030nm) was also tested with 1mm thick fused silica samples: setting the laser at 100kHz, 30 pulses (25W average power), exposure 60ms, via-holes through the entire 1 mm thickness were obtained. An impressive form factor of 38,5 was reached: the holes are straight and crack-free both at the entrance/exit (Fig. 10a) and along the propagation (Fig. 10b). The corresponding ablation rate is 0.02 mm3/W/min.

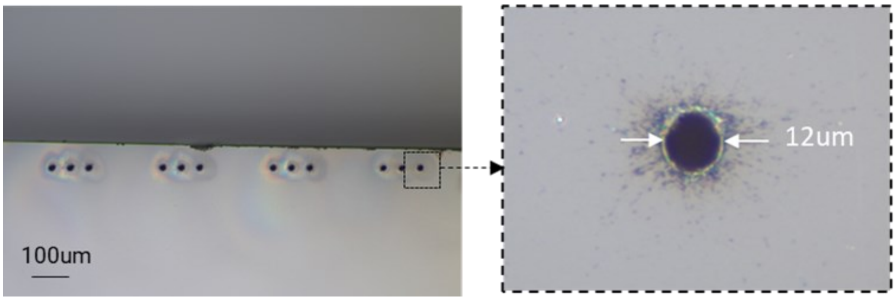

Fig. 8. Optical image of 1mm thick fused silica top view showing a series of crack-free and reproducible holes at 515nm, 2kHz, 1000pulses, 1ms.

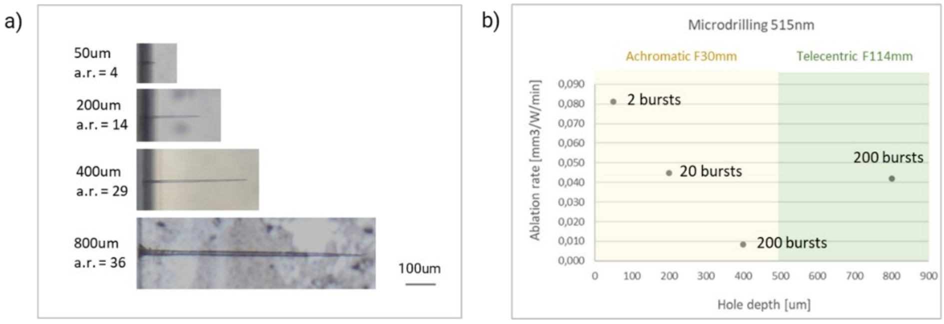

Fig. 9. (a) Cross-section of blind holes in 1mm thick fused silica samples at increasing depth and aspect ratio obtained at increasing number of bursts (i.e. drill time), according to the plot in (b). Laser settings: 515nm, 2kHz, 1000pulses.

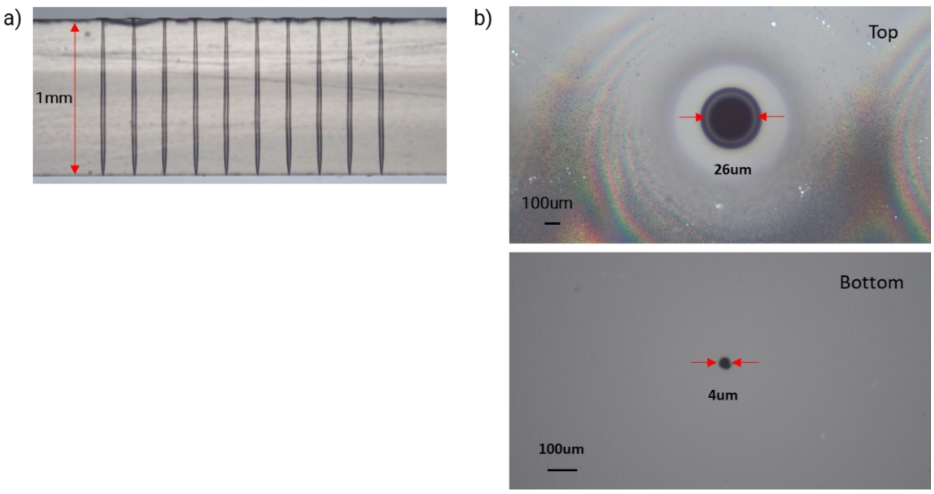

Fig. 10. (a) Cross-section optical image of via holes through 1mm thick fused silica sample: 1030nm, 100kHz, 30 pulses, 60ms drill time. Form factor 38,5, “v” shape. (b) Top and bottom view of the hole entrance/exit, showing exceptional crack-free feature.

3.3. Semiconductors

We extended our study to multilayer semiconductor substrates. We study the specific ablation rate for both silicon (Si) wafers and silicon carbide (SiC). Using optimized burst parameters (2kHz, 100pulses), we successfully drilled crack-free via holes up to 570 um (Fig. 11) deep in Si and 350um in SiC (Fig. 12). Specific ablation rate ⩾ 2,8 mm3/W/min in for Si and ≥ 3,2 mm3/W/min for SiC were reached. These results highlight the potential for industrial microfabrication applications where thermal stress and material integrity are critical.

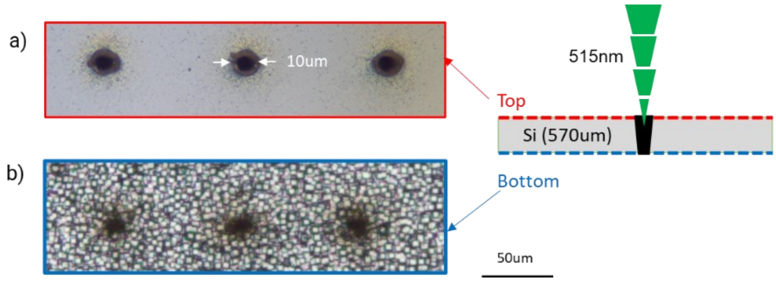

Fig. 11. (a) Burst power vs. fluence plot for Cu. (b) Cu engraved morphology evolution at decreasing burst fluences.

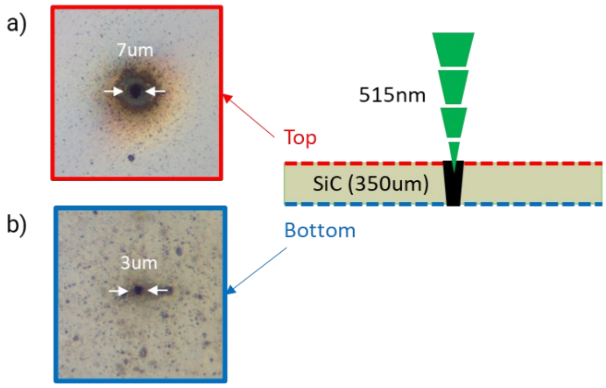

Fig. 12. (a) Ablation rate vs. number of pulses in the burst for Cu sample. (b) Cu engraved morphology evolution at increasing number of pulses.

4. Conclusions and perspectives

In this work, we have presented the results of metal engraving using the FEMTOFLASH laser, based on GHz fs burst technology. The unique patented laser's design is characterized by its compactness and exceptional flexibility, enabling precise control over key burst parameters such as repetition rate, pulse energy, and number of pulses per burst.

This flexibility allows the laser system to be tailored to diverse customer requirements across various laser micromachining applications. In this work we focused on glass percussion drilling applications.

In borosilicate glass displays, we achieved shallow pockets with diameters below 10 µm at low pulse counts, and larger holes up to 20 µm at higher pulse numbers, maintaining crack-free quality even with increased debris. Using the 100 W version at 1030 nm, both blind and through holes were drilled in 1 mm thick borosilicate samples, demonstrating scalable and robust processing with controllable aspect ratios and high ablation rates.

For fused silica, operating in a low burst number regime known to enhance efficiency (Balage, 2023), we produced crack-free holes with diameters around 10–12 µm and aspect ratios ranging from 4 to 36. Adjusting focal spot size further optimized drilling depth and efficiency. The 100 W laser also enabled drilling of straight, crack-free via holes through 1 mm thick fused silica in 80ms of exposure time. In recent experiments, drilling depths up to 2 mm was achieved.

Extending the study to semiconductor materials, we characterized the ablation rate for silicon and silicon carbide, achieving crack-free via holes up to 570 µm and 350 µm depth, respectively. Ablation rates of ≥ 2.8 mm^3/W/min for silicon and ≥ 3.2 mm^3/W/min for silicon carbide demonstrate excellent material removal efficiency with minimal thermal damage.

Overall, our results confirm that GHz-burst femtosecond laser technology, combined with arbitrary burst shaping and wavelength versatility, offers a powerful, scalable, and industrially viable solution for high-quality, high-throughput microdrilling in fragile and demanding materials. This work opens new opportunities for further advancements in ultrafast laser processing for next-generation glass and semiconductor microfabrication.

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