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GHz femtosecond bust laser for high-quality and efficient deep milling

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Abstract

High-quality and efficient cavity milling of tens of microns depth is underexplored but highly relevant in industrial applications. In this work, we present an innovative approach using a compact femtosecond GHz burst laser for cavity milling of different metals. We perform engravings at different depths (30-100 µm), systematically varying the burst parameters and analyzing the ablation efficiency and quality as the engraving depth increases. We also characterized the morphology of the engraving (e.g. edge recast and bottom cavity roughness) across different laser settings, to ensure an optimal balance between efficiency, quality and depth. Finally, we optimize the post-milling processes, such as polishing and whitening. We demonstrate that by optimizing burst parameters, it is possible to achieve efficient and high-quality milling at various depths. Furthermore, an optimized initial engraving strategy is essential for obtaining high-quality surface finishing, even at the greatest depths achieved.

Keywords: GHz-burst; fs; deep engraving; ultrafast laser processing; metals

1. Introduction

Femtosecond (fs) laser micromachining using GHz burst modes has emerged as a transformative approach for ultra-precise, cold processing of materials. Compared to conventional MHz systems—where each pulse is delivered at microsecond-scale intervals—GHz bursts introduce nanosecond delays between femtosecond pulses within a single burst. This ultrafast temporal technology promotes residual energy coupling, enhancing nonlinear absorption and ablation efficiency, while reducing heat diffusion into the surrounding material (incubation effect). As a result, GHz bursts enable highly localized, non-thermal ablation with minimal heat-affected zones (HAZ) (Gräf, 2021; Lorbeer et al., 2019).

Numerous studies have demonstrated the advantage of the GHz regime over MHz, particularly for metal engraving, microstructuring, and finishing. The ablation-cooled model introduced by Kerse et al., 2026, was a key milestone, showing that energy delivered in a train of closely spaced low-energy pulses can significantly improve machining precision and surface quality. Bonamis (Bonamis et al., 2019; Bonamis at al. 2020) and López (Lopez at al., 2020) extended these results to metals such as copper, stainless steel, and aluminum, demonstrating that burst duration and pulse count per burst are critical for optimizing both ablation efficiency and surface morphology.

Further comparative studies have confirmed that GHz bursts can achieve higher specific removal rates and smoother surfaces than MHz bursts, which tend to induce thermal accumulation, rougher textures, and reduced edge quality (Zemaitis et al., 2024). These insights are now driving innovation in industrial applications requiring high throughput, controlled depth, and minimal thermal effects.

In this context, we present a novel fs laser system based on GHz burst technology that introduces a key innovation: an exceptionally compact form factor with fully embedded control electronics. The system offers a high flexibility level of key burst parameters, including intra-burst repetition rate, pulse number, and burst energy distribution, enabling users to finely tune the process for a range of materials and application requirements.

In this study, we focus on engraving and marking of metals, including stainless steel, brass, and copper, to demonstrate how flexible control of burst dynamics translates into superior results in terms of:

- Engraving depth;
- surface finish (white or polished appearance);
- edge sharpness and roughness control;
- recast suppression through continuous GHz operation (“full pulses” mode).

Our results confirm that low-pulse-count, low-fluence bursts yield high-quality and fine finishing even at significant engraving depths (30–100 µm), which is essential for applications in industrial sectors as luxury and semiconductor.

2. Materials and methods

2.1. Laser source

The experiments were performed using FEMTOFLASH 20 laser (Lithium Lasers, 20 W, 0,8 GHz) from Lithium Lasers, a compact fs laser based on GHz burst technology (Fig. 1). The laser has a unique patented design, operating in GHz burst mode natively: it is based on a high-frequency and high-power solitonic mode-locking oscillator, with a single-stage amplification step and an AOM for burst modulation.

The system is designed for industrial micromachining applications and combines ultra-compact footprint with exceptional configurability. It is available in both infrared (IR) and green wavelengths and delivers high pulse repetition rates up to 0.8 GHz, with a maximum average power of 20 W. In this work we use the IR (1030nm) wavelength.

The laser includes fully embedded control electronics in a highly compact box - 420×294×145mm - (Fig. 2a): this unique feature ensures ease of integration and deployment in industrial environments.

The other key strength of this system lies in its flexibility and fine-tunability (Fig.3). Unlike conventional fs lasers, FEMTOFLASH 20 allows independent modulation of key burst parameters, 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-based laser technologies.
- Intra-burst energy distribution: the energy distribution within the burst can be changed, allowing for the thermal gradient on the work piece.

This high flexibility enables precise control over the laser–material interaction dynamics, allowing optimization of both material removal efficiency and surface quality across a wide range of processing conditions. In particular, the system supports operation in discrete burst regimes as well as continuous GHz burst trains (“full pulses mode”), which are especially effective for applications requiring minimal recast and high-quality surface finishing.

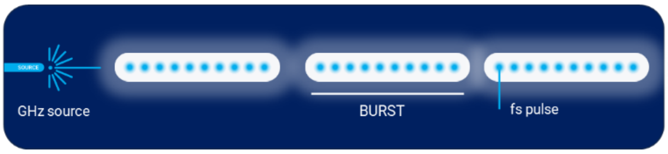

Fig. 1. GHz fs FEMTOFLASH laser technology.

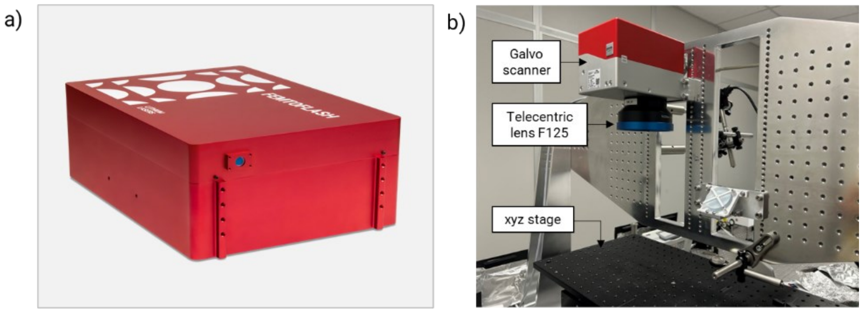

Fig. 2. (a) FEMTOFLASH laser from Lithium Lasers, (b) Galvo head in the application laboratory.

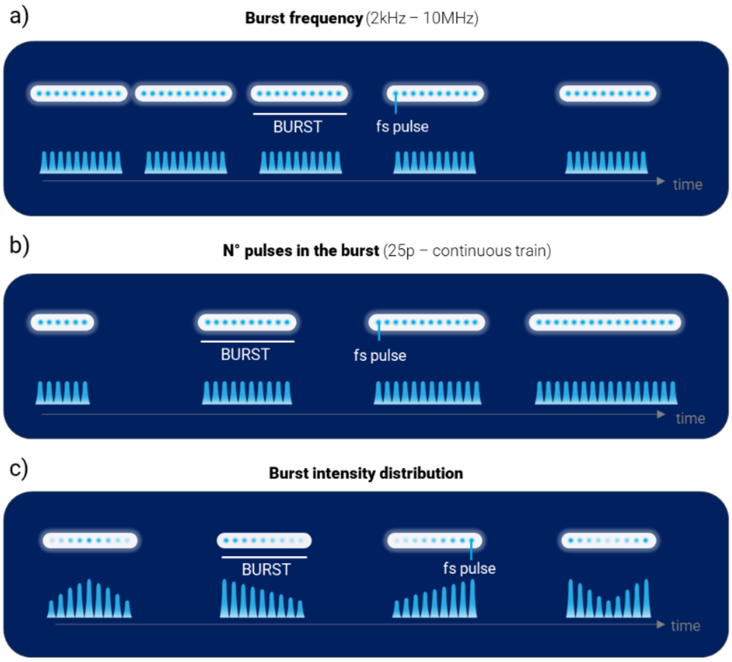

Fig. 3. Modulation of different laser parameters: (a) Burst frequency, (b) number of pulses in the burst, (c) Burst intensity distribution.

2.2. Experimental setup

The engraving tests on metals have been performed in our fully equipped application laboratory, where we study customer requirements and we find out final laser settings tailored for each specific process.

The laser was used in combination with a galvanometric scanner (Fig. 2b) equipped with an F-theta lens (F125mm). Beam focusing conditions were adapted depending on the application, with spot sizes and working distances optimized to control ablation geometry and efficiency. All experiments were performed in ambient air. The sample motion and pulse overlap were controlled via synchronized motion stages and software-defined scan strategies.

2.3. Materials under test

We studied laser engraving on various metallic samples:

- Stainless steel (AISI 316L): target engraving depths up to 100 µm with uniform white finishing for luxury application.
- Brass (CuZn37): target engraving depths up to 100 µm with uniform bright/golden finishing for luxury application.
- Copper (pure): engraving and scribing for semiconductor applications

The laser parameters were systematically varied to identify optimal combinations for different performance targets, including engraving depth, edge quality, surface morphology, and visual finish. A particular focus was placed on reducing thermal effects, controlling the roughness of the engraved surfaces, and minimizing recast formation.

3. Results and discussion

This section presents the experimental results obtained using the FEMTOFLASH laser system for the micromachining of stainless steel, brass, and copper. The tests were carried out to assess the laser's performance in response to specific industrial application requirements, with a focus on processing quality, repeatability, and ablation efficiency for each material. The process parameters were selected to reflect realistic operating conditions compatible with advanced manufacturing needs in marking, engraving, and microstructuring applications.

3.1. Stainless steel

We investigated stainless steel engraving for applications in the luxury (watch and jewelry) sector, where the process must combine high **controlled depth**, **high throughput**, and a **white, uniform finish**. The target was to reach engraving depths up to **100 µm** while exhibiting a clean and bright surface appearance, which remains consistent at different viewing angle.

We conducted a systematic study by engraving 2x2mm2 areas and varying burst parameters, particularly the number of pulses per burst and the burst energy. We first mapped burst parameters vs. engraving depth (Fig. 5) at different burst frequency (300, 400 and 800 kHz), identifying a maximum engraving efficiency of 0,144 (mm^3/W/min), in line with other GHz fs lasers (Bonamis et al., 2020).

Then we studied how surface morphology of the engraved area affects the final white finish, playing with the number of pulses in the burst. We found that controlling the roughness of the engraved area (by using a low number of pulses) is crucial to achieve a white finishing that can meet the expectations.

The experiments revealed a strong correlation between **surface morphology** and the **visual appearance** of the engraved areas. Key findings include:

- Increasing the number of pulses per burst (>75) tends to increase roughness, which degrades the white finish (Fig. 6a).
- A low number of pulses per burst favors surface smoothness (25-75), enhancing the reflectivity and uniformity of the white appearance (Fig. 6b).

Edge quality is also critical in the laser process assessment. The edges of the cavities must be smooth to the touch, with no perceptible recast. We demonstrated that a subsequent low-energy polishing step, using a continuous GHz burst train, was effective in removing recast material and smoothing the cavity edges, resulting in a tactilely smooth finish without noticeable edge defects (Fig. 7).

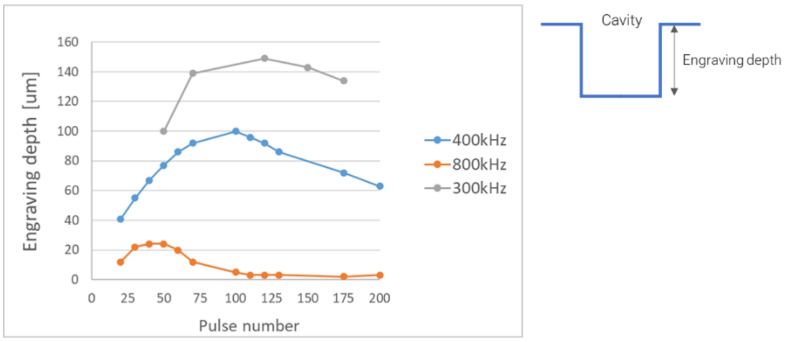

Fig. 5. Engraving depth vs. number of pulses in the burst at different burst frequency for stainless steel: 300 kHz, 400 kHz and 800 KHz (50 passes).

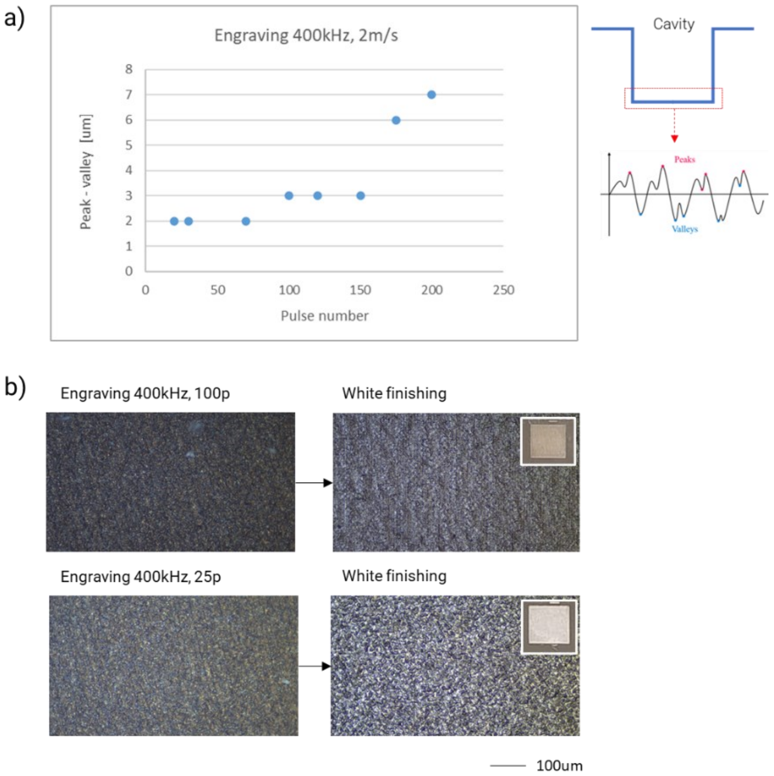

Fig. 6. (a) Evaluation of the roughness vs. number of pulses for stainless steel. (b) Optical images of 100 um deep engraved areas: the starting roughness influences the final finishing (photo of the $2x2\ mm^2$ obtained squares in the insert).

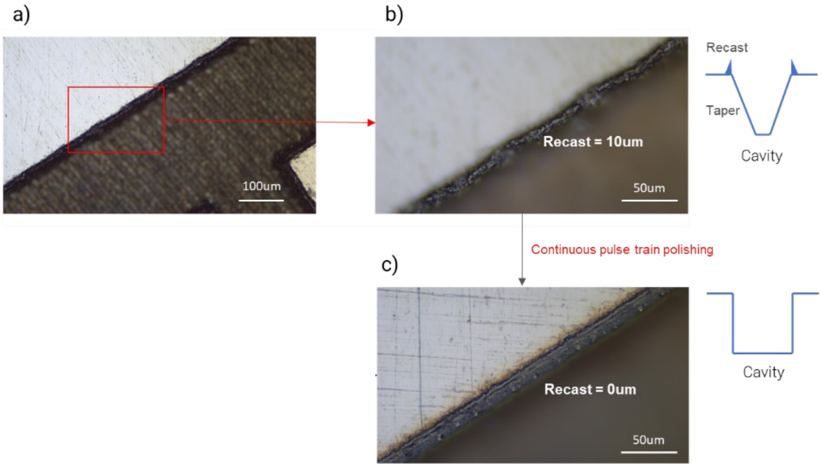

Fig. 7. Optical images of a stainless-steel edge detail (a,b) before and (c) after “full pulses mode” polishing.

3.2. Brass

Brass samples were processed to explore the combination of deep engraving and surface finish customization, targeting applications in decorative and industrial components.

By tuning the burst structure and energy, we achieved:

- ablation rate of 0,544 (mm3/W/min), comparable with literature results (Leggio et al., 2023),
- depths reaching several hundred microns (see cavities in Fig. 8), at 200kHz and 100 pulses in the burst. By changing the position of the laser focus with respect to the samples, different morphologies (and colors) of the engraved areas were obtained.
- Control over surface appearance: depending on the burst configuration, the final surface could be tuned to exhibit a smooth white or golden finish (Fig. 9).

This demonstrated the ability of our laser system to balance material removal rate with visual quality, providing application-specific laser recipes based on customer requirements.

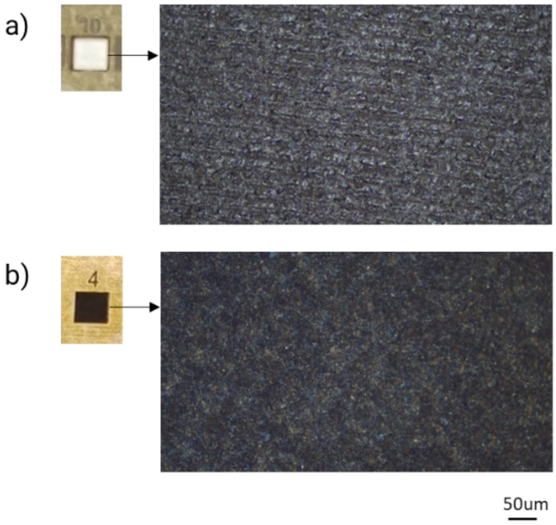

Fig. 8. Optical images of brass engraved areas at two different focusing conditions, corresponding to (a) white and (b) black finishing, visible in the photos on the left.

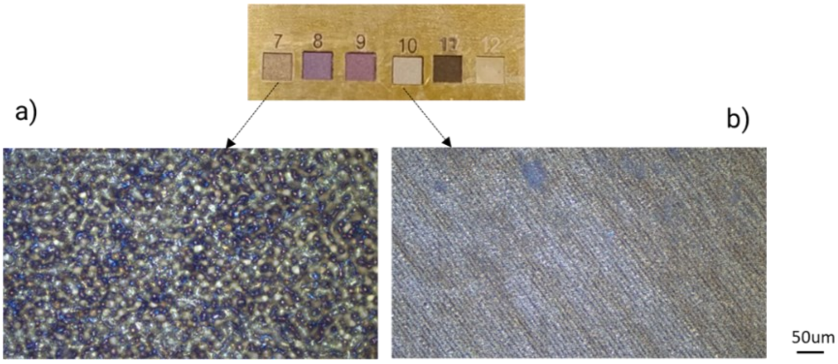

Fig. 9. Optical images of brass morphology corresponding to two different post-engraving laser finishing: (a) goldened and (b) white.

3.3. Copper

Copper engraving was studied for applications in the semiconductor industry, where the focus shifts from visual appearance to functional performance, such as depth control and clean edge definition.

The main goal was to optimize the process to fabricate clean scribe lines with high dimensional accuracy. To this end, we systematically varied:

- Burst energy to investigate the fluence threshold for clean ablation. Ablation fluence threshold of 13,1 J/cm2 has been identified, corresponding to 1,5W average power. Below this value, no morphology modification in copper surface has been observed (Fig. 10).
- Number of pulses per burst to evaluate the impact on remelting and debris formation.

Key observations:

- Increasing the number of pulses per burst resulted in excess remelt, reducing process efficiency and contaminating the surface (Fig. 11).
- A lower number of pulses, in combination with properly tuned energy, ensured clean ablation, minimal redeposition, and gentle material removal.

This allowed us to define a robust burst parameter set for copper, optimized for depth-controlled micromachining without compromising edge quality or cleanliness—critical for multilayer semiconductor processing.

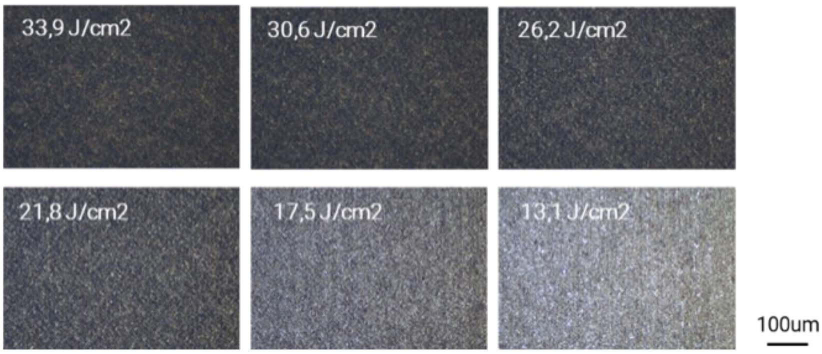

Fig. 10. Copper morphology dependence on burst fluences for 2x2mm^2 engraved areas.

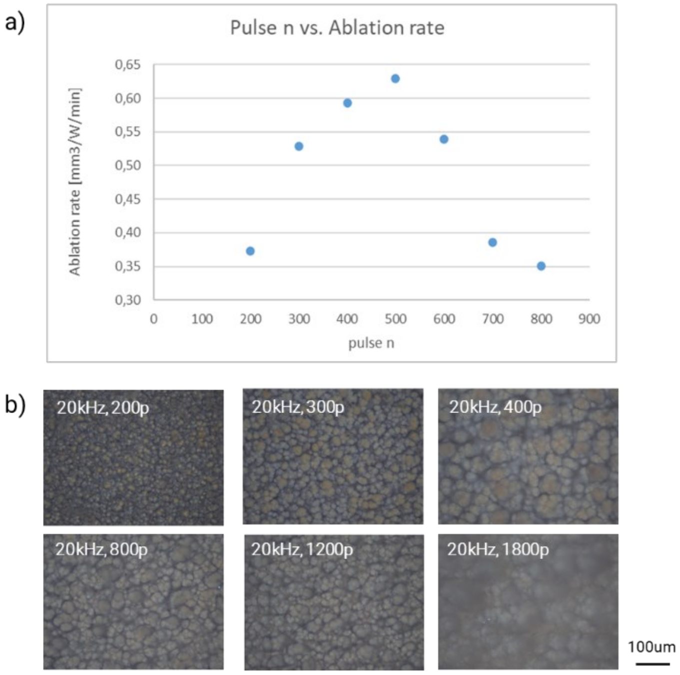

Fig. 11. (a) Ablation rate vs. number of pulses in the burst for Cu sample. (b) Cu engraved morphology evolution at increasing number of pulses.

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. We demonstrated its capabilities through a series of engraving and marking experiments on stainless steel, brass, and copper substrates.

Material behavior was thoroughly characterized in terms of engraving efficiency, which is comparable to that of other GHz femtosecond laser systems currently available (Bonamis et al., 2020; Leggio et al., 2023; Žemaitis et al., 2024). Importantly, the laser's cold ablation regime, achieved through low-intensity, high-frequency pulses, ensures high-quality surface finishing while reaching engraving depth up 100um, with minimal thermal damage.

Moreover, the unique ability of the FEMTOFLASH laser to operate in a continuous GHz burst train mode ("full pulses mode") offers significant advantages in eliminating recast and producing superior edge quality and surface smoothness.

These results confirm the potential of GHz femtosecond burst lasers as versatile and high-performance tools for precision industrial micromachining, addressing the stringent demands of both aesthetic and functional applications.

As a perspective, we have developed a new version of the FEMTOFLASH laser with an increased average power of **100 W (FEMTOFLASH 100)**, while maintaining the same compact footprint as the 20W version. This upgraded system will be tested in future studies to evaluate potential improvements in ablation rate and overall processing throughput, aiming to further enhance industrial applicability and efficiency.

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