Will GHz burst mode create a new path to femtosecond laser processing?
Koji Sugioka

Highlights:
- This perspective gives the history, current status, and future challenges and prospects of this new strategy to answer the question, ‘will GHz burst mode create a new path to femtosecond laser processing?’

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Will GHz burst mode create a new path to femtosecond laser processing?

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Abstract
The GHz burst mode of femtosecond laser pulses can significantly improve ablation efficiency without deteriorating ablation quality. However, various parameters involved in GHz burst mode make it difficult to optimize the processing for practical implementation. In this Perspective, the author gives the history, current status, and future challenges and prospects of this new strategy to answer the question, ‘will GHz burst mode create a new path to femtosecond laser processing?’

Femtosecond lasers have opened up new avenues in materials processing due to their distinct features, such as ultrashort pulse width and extremely high peak intensity, which provide superior performance for machining diverse materials to other conventional lasers [1, 2]. Specifically, one of the most important features of femtosecond laser processing is its ability to perform ultrahigh precision micro- and nanofabrication with high quality by suppressing the formation of heat-affected zones (HAZs). Femtosecond lasers are being widely used for commercial applications, including micromachining and trimming of electronic, automotive, and medical components; scribing and dicing of glass and sapphire substrates for smart phones and displays; fabricating anti-reflection surfaces by nanostructuring Si solar cells, scribing and patterning of copper indium gallium selenide, copper indium selenide, and inorganic solar cells; defect repair and edge cutting of micro-light emitting diode displays; and fabrication of medical stents. Improving throughput is urgently demanded to further accelerate their commercialization and industrial applications. One can imagine that throughput can be easily increased by increasing the intensity and/or repetition rate of laser pulses. However, higher intensities suffer from plasma shielding, reducing the ablation efficiency and often inducing thermal damage due to the deposition of excess energy [3]. A repetition rate higher than several hundred kHz induces heat accumulation produces large HAZs, which is not suitable for high precision or high-quality microfabrication [4].

Ilday’s group recently demonstrated that bursts of femtosecond laser pulses with GHz repetition rate can enhance the ablation efficiency with improved ablation quality, as shown in figure 1 [5]. They claimed that the target material is ablated before the residual heat deposited by previous pulses diffuses away from the processing region to increase ablation efficiency (one-order higher). They further claimed that the physical removal of ablated materials carries away the thermal energy contained in the ablated mass, resulting in high-quality ablation with no thermal effect. They call this process ablation cooling. These results have...
Figure 1. Laser ablation of human dentine by the conventional scheme ((a), 1 kHz uniform repetition rate) and GHz burst mode ((b), 1.7 GHz intraburst repetition rate). Although both schemes avoid thermal damage at sufficiently low average powers, the GHz burst mode creates approximately six times deeper ablation crater despite about a 12 times lower pulse energy. (c) and (d) When the repetition rate, average power and scanning speed are simultaneously increased by a factor of 25, the conventional scheme results in thermal damage, whereas the GHz burst mode completely avoids thermal effects and achieves much higher ablation rate, despite using a 25 times lower pulse energy. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature, Kerse et al [5]. Copyright (2016), Nature Publishing Group, a division of Macmillan Publishers Limited. All Rights Reserved.
overturned common sense and significantly impacted the community of laser materials processing.

Despite the community’s interest in GHz burst mode, the lack of laser sources has made it more difficult for researchers to perform experiments that further explore this process. However, some laser manufactures have started to develop femtosecond laser systems that can operate in GHz burst mode, allowing some research groups to investigate GHz burst mode ablation of metals, such as copper, stainless steel, and aluminum \([6–12]\), as well as semiconductors and dielectric materials, such as silicon, silicon carbide, fused silica, and Kapton \([6–8, 13]\). Typically, GHz burst mode creates ablated surfaces with better quality as compared with the conventional single mode \([7, 11, 13]\). The superior surface quality may rely on ablation cooling. However, GHZ enables gentle heating and melting in a more controlled manner to create smoother ablated surfaces because resolidified layers were evidently observed at the ablated surfaces of some materials, which is regarded as more possible mechanism. Additionally, optimizing parameters, such as the number of intra-pulses, pulse-to-pulse interval (repetition rate of intra-pulses), and the burst energy (total energy of all intra-pluses in a burst), is important to achieve higher ablation quality. On the other hand, ablation efficiency significantly depends on the type of material. Specifically, compared to the conventional single mode, GHZ burst mode achieves higher ablation efficiency for semiconductors and dielectrics, including silicon, silicon carbide, fused silica, and Kapton, and achieves lower ablation efficiency for metals \([8, 11, 13]\). The author speculates that the ablation efficiency should be closely related to the absorption process of laser pulses by the materials. For bandgap materials, laser energy is first absorbed by bound electrons in the valence band to generate free electrons in the conduction band. The excited free electrons can efficiently absorb subsequent pulses in the burst to increase the ablation efficiency. In contrast, for metals, free electrons always absorb the laser energy. Laser energy discretely dispersed in the burst may inhibit efficient energy deposition due to the diffusion or dissipation of heat generated by preceding pulses. Plasma shielding is another important factor affecting ablation efficiency, since plasma dynamics depend on the materials ablated.

GHz burst mode processing involves various parameters, such as the number, duration, and energy of intra-pulses as well as the time interval of each intra-pulse. Additionally, the different energy distributions of intra-pulses in the bursts (e.g. gradually increased, gradually decreased, or mountain-shaped distribution of intra-pulse energy) should provide different results even for the same burst energy. GHZ burst in MHz burst (BiBurst) further offers a unique scheme for more practical use \([10]\). The research on GHZ burst mode processing is still in its infancy, and the accumulation of a massive amount of data with different parameters and different materials is necessary. A fully automated data acquisition system for GHZ burst mode processing combined with deep learning based on collected big data using an artificial intelligence is a good solution to accelerate practical implementation of this process \([14]\). A theoretical approach based on physics theories is also important; although, the huge parameters present many challenges. Another key factor is the development of a high-performance laser system which can easily, flexibly adjust parameters in the GHz bursts mentioned above.

The relatively slow processing speed of femtosecond laser ablation is a bottleneck for industrial implementation, which will be overcome by significantly enhancing ablation efficiency without deteriorating ablation quality with GHz burst mode. Furthermore, GHZ burst may offer a new possibility for processing other than ablation. In particular, the capability of gentle heating and melting in a controlled manner will be effective for processing based on thermal reactions, such as microbonding, crystallization, and polishing. Applying to the processing
specific to femtosecond lasers, including two-photon polymerization, internal optical waveguide writing, and the formation of high spatial frequency laser induced periodic structures, could produce distinct features. Thus, the author believes that GHz burst mode will open new paths to femtosecond laser processing.

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