Opto-Electronic Advances

News & Views

December 2024, Vol. 7, No. 12

DOI: 10.29026/oea.2024.240222 CSTR: 32247.14.oea.2024.240222

High performance laser induced plasma assisted ablation by GHz burst mode femtosecond pulses

Jingbo Yin[1,2], Yulong Zhao[1] and Minghui Hong[1,2]*

High performance laser micromachining based on the combination of GHz burst mode femtosecond pulses irradiation and laser induced plasma assisted ablation can open a new avenue for high-quality and high-efficiency micromachining of single crystalline sapphire.

Yin JB, Zhao YL, Hong MH. High performance laser induced plasma assisted ablation by GHz burst mode femtosecond pulses. *Opto-Electron Adv* **7**, 240222 (2024).

Transparent materials, such as sapphires, diamonds, and quartzs, have excellent material properties[1]. High hardness, high chemical stability and unique optical properties make it valuable in industrial production and scientific research, but difficult to be processed[2,3]. Laser induced plasma assisted ablation (LIPAA) is one of the relatively simple and effective approaches[4]. Nanosecond (ns) lasers are typically used in LIPAA due to its relatively long pulse duration[5]. The plasma induced by the laser ablation of target is generated within tens to hundreds of picoseconds (ps) and continuously expands in ns scale[6]. So every ns laser pulse replenishes the plasma induced to make it strong enough to ablate the substrate. This makes ns-LIPAA high ablation efficiency. Because of the strong thermal effect of the ns laser ablation, the feature size and surface roughness of the ns-LIPAA are relatively large. Ultrafast laser is expected to produce high-precision LIPAA. Since the pulse duration of femtosecond (fs) laser is extremely short, its pulse is ended before the formation and expansion of the plasma generated by this fs pulse. This results in the plasma not strong enough to ablate the substrate but depositing a layer of metal film on the substrate surface. Therefore, one solution is to apply a high laser fluence in the ablation, which also causes a significant decrease in ablation quality, the other is by a dual-beam fs-LIPAA[7]. In the dual-beam LIPAA, plasma induced by the 1st pulse loses the energy during flying, so metal nanoparticles included are deposited on the substrate surface. The ablation takes place by the absorption of the 2nd laser pulse energy by the deposited nanoparticles. Such processing method is complex and inefficient. With the development of laser technology, GHz burst mode fs lasers have attracted much attention in various material processing fields[8,9]. Since its pulse interval is only several hundred ps, GHz burst mode is expected in the fs-LIPAA to realize the interaction between laser and laser-induced plasma.

In the recent work published in *Opto-Electronic Science*[10], Prof. Koji Sugioka and his team at RIKEN Center for Advanced Photonics (RAP) proposed a high performance LIPAA strategy based on GHz burst mode fs pulses. In the burst mode, the time interval between the adjacent pulses of the pulse trains is several hundred ps. The authors demonstrated that this moderate pulse interval

[1]Pen-Tung Sah Institute of Micro-Nano Science and Technology, Xiamen University, Xiamen, 361005, China; [2]Discipline of Intelligent Instrument and Equipment, Xiamen University, Xiamen, 361005, China.

*Correspondence: MH Hong, E-mail: elehmh@xmu.edu.cn

Received: 20 September 2024; Accepted: 27 September 2024; Published online: 16 December 2024

allows for direct interaction between the laser pulses and the laser-induced plasma. This interaction enhances both the ablation quality and efficiency, making the process more effective than traditional methods, such as single-pulse mode fs laser direct ablation, single-pulse mode fs-LIPAA, and ns-LIPAA.

Figure 1 presents the experimental setup for the GHz burst mode fs-LIPAA process. Unlike the traditional single-pulse mode, the GHz burst mode delivers a series of intra-pulses within a burst, with the time interval of 205 ps (corresponding to a 4.88 GHz repetition rate). This design significantly enhances the interaction between

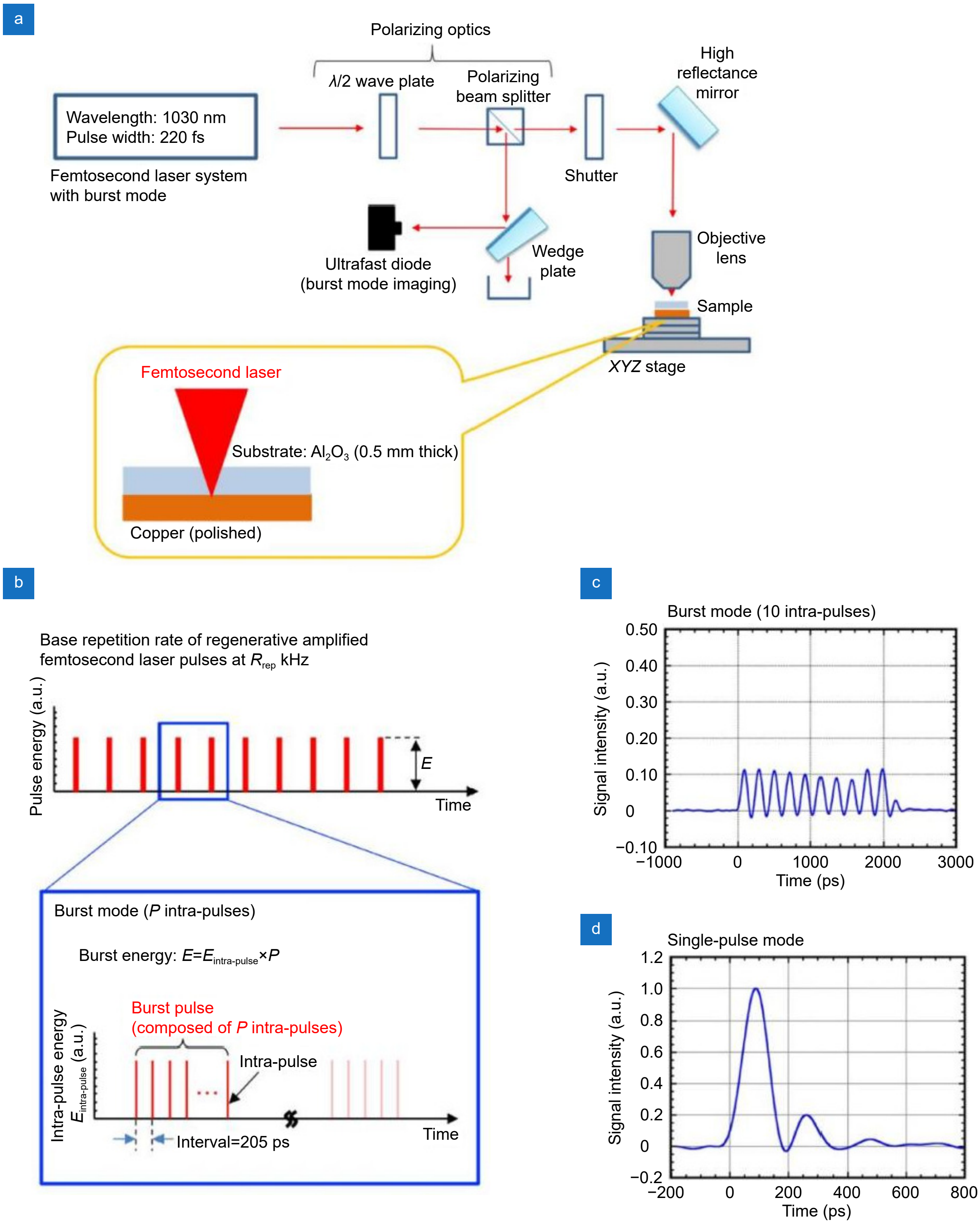

Fig. 1 | Experimental setup for the GHz burst mode fs-LIPAA process.

laser pulses and the generated plasma. In the experiment, a c-axis (0001) oriented sapphire substrate is placed in contact with a copper target. The laser beam passes through the sapphire and focuses on copper surface, generating a plasma. The subsequent pulses in the burst directly interact with this plasma, greatly increasing the ablation efficiency. In addition, the GHz burst mode has better ablation quality than the single-pulse mode. It is because the plasma induced by the previous intra-pulses in the burst mode can induce effective absorption at the rear surface of sapphire by the subsequent pulses. Higher absorption rate is essential to obtain better ablation quality. For the single-pulse mode LIPAA, the direct interaction between laser and plasma is impossible because of the long interval between adjacent pulses. The ns laser can interact with the plasma generated by its own excitation within the pulse duration, which has high processing efficiency. However, the processing quality of ns-LIPAA for sapphire and other wide band gap materials is significantly lower than GHz burst mode fs-LIPAA. In general, the GHz burst mode fs-LIPAA solves the problem that processing efficiency and processing quality cannot be balanced.

High repetition rate femtosecond laser has shown its unique advantages in many material processing fields[11,12]. Introducing GHz burst mode fs laser into LIPAA processing represents a promising approach to micromachine hard transparent materials. The ability to reduce the ablation threshold and increase ablation efficiency while maintaining high-quality surface finishes opens up new possibilities for the manufacturing of advanced optical and electronic components. The GHz burst mode's high precision and reduced energy requirement make it attractive for large-scale manufacturing where both quality and efficiency are paramount. Additionally, one of the most promising aspects of this research is the scalability to process other transparent materials. While the study focused on sapphire, the same principles could be applied to materials, such as quartzs, diamonds, and transparent ceramics, which are also difficult to be machined with conventional methods[13,14]. Moreover, the potential for further enhancement using shaped laser beams (e.g., Bessel beams) or adaptive optics could lead to even higher levels of precision and efficiency, expanding the applications of the GHz burst mode LIPAA. Its success with sapphire suggests that future studies may focus on processing different materials, expanding its applicability across a broader range of sectors.

References

1. Wang SF, Zhang J, Luo DW et al. Transparent ceramics: processing, materials and applications. *Prog Solid State Chem* **41**, 20–54 (2013).
2. Liu HG, Lin WX, Hong MH. Hybrid laser precision engineering of transparent hard materials: challenges, solutions and applications. *Light Sci Appl* **10**, 162 (2021).
3. Yan TY, Ji LF. Ultrafast laser filamentation in transparent solids. *Ultrafast Sci* **3**, 0023 (2023).
4. Zhang J, Sugioka K, Midorikawa K. Direct fabrication of microgratings in fused quartz by laser-induced plasma-assisted ablation with a KrF excimer laser. *Opt Lett* **23**, 1486–1488 (1998).
5. Hong MH, Sugioka K, Lu YF et al. Laser microfabrication of transparent hard materials and signal diagnostics. *Appl Surf Sci* **186**, 556–561 (2002).
6. Zhao YL, Yan TY, Hong MH. Enhancement of laser-induced plasma-assisted ablation of glass substrate via interacting spatial double laser pulse irradiation. *Opt Laser Technol* **180**, 111588 (2025).
7. Hanada Y, Sugioka K, Miyamoto I et al. Double-pulse irradiation by laser-induced plasma-assisted ablation (LIPAA) and mechanisms study. *Appl Surf Sci* **248**, 276–280 (2005).
8. Kerse C, Kalaycıoğlu H, Elahi P et al. Ablation-cooled material removal with ultrafast bursts of pulses. *Nature* **537**, 84–88 (2016).
9. Park M, Gu YR, Mao XL et al. Mechanisms of ultrafast GHz burst fs laser ablation. *Sci Adv* **9**, eadf6397 (2023).
10. Obata K, Kawabata S, Hanada Y et al. High performance micromachining of sapphire by laser induced plasma assisted ablation (LIPAA) using GHz burst mode femtosecond pulses. *Opto-Electron Sci* **3**, 230053 (2024).
11. Lin ZY, Liu K, Cao T et al. Microsphere femtosecond laser sub-50 nm structuring in far field via non-linear absorption. *Opto-Electron Adv* **6**, 230029 (2023).
12. Yin JB, Li YZ, Chen ZW et al. Formation of armored silicon nanowires array via high-repetition-rate femtosecond laser oxidation for robust surface-enhanced Raman scattering detection. *ACS Appl Mater Interfaces* **16**, 48667–48675 (2024).
13. Jia LM, Cheng L, Zheng W. 8-nm narrowband photodetection in diamonds. *Opto-Electron Sci* **2**, 230010 (2023).
14. Wang Z, Zhang B, Tan DZ et al. Ostensibly perpetual optical data storage in glass with ultra-high stability and tailored photoluminescence. *Opto-Electron Adv* **6**, 220008 (2023).