Burst-mode femtosecond ablation in Copper and Lexan

Craig W. Siders, Martin Richardson, Nikolai Vorobiev, Ty Ohlmstead, Rob Bernath, and Tina Shih
The School of Optics/CREOL, University of Central Florida, Orlando Florida 32816-2700
407-823-6906 (Office), 407-823-4339 (Fax), csiders@creol.ucf.edu

Abstract: We present the results of a comparative study of 850-nm femtosecond ablation using single and eight-pulse 30-ns duration bursts with 4-mJ integrated energy. Five-fold increase in the copper ablation rate in ambient air was seen.

OCIS codes: (140.3390) Laser materials processing; (320.2250) Femtosecond phenomena

Femtosecond ablation of both absorbing and transparent materials has several distinct advantages [1-3]. Firstly, the threshold energy fluence for the onset of damage and ablation is orders of magnitude less than for traditional nanosecond laser machining. Secondly, by virtue of the rapid removal after excitation of material confined to approximately the optical penetration depth, femtosecond machined cuts are significantly cleaner and more precise, with comparatively little to no heat-affected zone. However, given the shallow penetration depths in many materials of interest, especially metals, this inherently limits ablation rates to 10-100 nm/pulse. A simple method to increase the ablation rate by increasing the pulse energy soon becomes counterproductive when the peak intensity exceeds the air ionization threshold. We present here the results of using multiple pulse bursts to significantly increase the per-burst ablation rate compared to a single pulse with the same integrated energy, while keeping the peak intensity of each individual pulse below the air ionization limit.

A table-top Cr:LiSAF chirped-pulse amplified laser system was used as the source of ~100-fs, multi-mJ pulses at 850-nm. An output-coupled regenerative/power amplifier followed by a pulse slicer and Michelson interferometer provided a eight-pulse burst of 30-nm duration and 4-mJ total energy. In single-pulse mode an equal amount of energy was used. The ablation experiments were performed in a vacuum chamber containing 127μm copper and lexan foils placed in the focal region of a 125-mm focal length lens and providing incident fluences of 2-200 J/cm^2. Experiments were performed under both ambient air and evacuated conditions.

As can be seen in Fig. 1, a significant increase in the ablation rate in air occurs with an 8-pulse 30-ns burst of 100-fs pulses compared to an equal-energy 100-fs single pulse. We attribute this to reduced ionization of air from the 8-fold reduction of peak intensity from $\sim 10^{15}$ W/cm2 (above air ionization threshold). Moreover, both the "elbow" and the rate of increase in the ablation rate with incident fluence are significantly increased. As figure 2 shows, this is a consequence of the logarithmic scaling of the ablation rate, $L(F) = \delta \ln[F/F_{th}]$, where δ is the energy deposition scale length (on the order of the optical penetration depth for femtomachining near the damage fluence F_{th} and greater at higher fluences due to fast carrier diffusion [4]). For n-pulses in a burst, both the fluence at the "elbow" – the cross-over point between shallow and deep energy deposition – and the slope of the curve are expected to increase by a factor n, if debris interaction with succeeding pulses in a bunch is negligible. Burst-mode ablation thus accesses the regime of precise micromachining achievable with just-above-threshold femtosecond pulses, but with an n-fold greater per-burst ablation rate it allows, *in air*, a greater machining/cutting rate.

CFF3

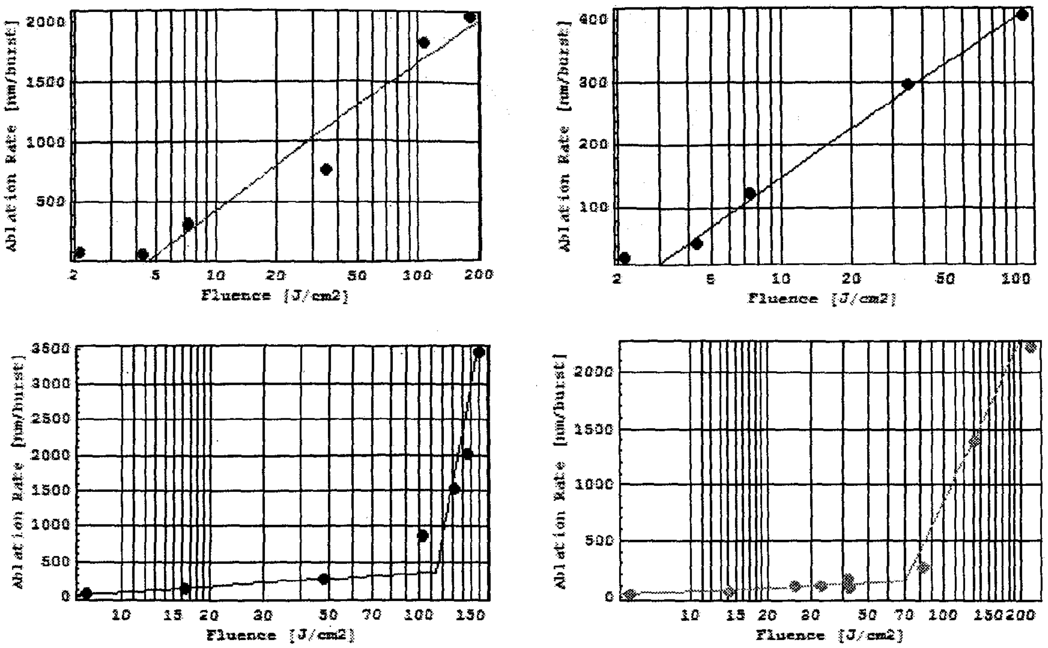

Fig 1: Ablation rate [nm/burst] for copper for single pulse (top row) and eight-pulse (bottom row) excitation. Two air pressures were used: 2-Torr (left column) and 760-torr (right column). Lines are logarithmic fits. Note the increased threshold and greater slope of the high-fluence part of the fits.

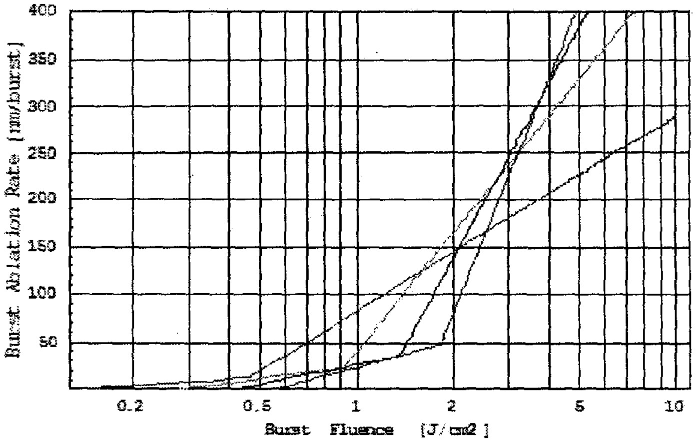

Fig 2: Theoretical ablation rate [nm/burst] for copper for single pulse, two-, three- and four-pulse excitation using the single-pulse damage threshold and energy deposition scale lengths from the literature [4].

[1] B. C. Stuart, *et al.*, "Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses," *Phys. Rev. Lett.*, vol. 74, pp. 2248-2251, 1995.

[2] P. P. Pronko, *et al.*, "Machining of Submicron Holes Using a Femtosecond Laser at 800- Nm," *Opt. Commun.*, vol. 114, pp. 106-110, 1995.

[3] B. N. Chichkov, *et al.*, "Femtosecond, picosecond and nanosecond laser ablation of solids," *Appl. Phys. A-Mater. Sci. Process.*, vol. 63, pp. 109-115, 1996.

[4] S. Nolte, *et al.*, "Ablation of metals by ultrashort laser pulses," *J. Opt. Soc. Am. B-Opt. Phys.*, vol. 14, pp. 2716-2722, 1997.