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Abstract

Ultrashort pulsed lasers can accurately ablate materials which are refractory, transparent, or are otherwise difficult to machine by other methods. The typical method of machining surfaces with ultrashort laser pulses is by raster scanning, or the machining of sequentially overlapping linear trenches. Experiments in which linear trenches were machined in alumina at various pulse overlaps and incident fluences are presented, and the dependence of groove depth on these parameters established. A model for the machining of trenches based on experimental data in alumina is presented, which predicts and matches observed trench geometry. This model is then used to predict optimal process parameters for the machining of trenches for maximal material removal rate for a given laser.

1. Introduction

Ultrashort pulsed lasers have demonstrated in recent years the capability to ablate accurately several materials of diverse composition. In materials with a significant band gap the energy is absorbed via multiphoton ionization and the following avalanche development making possible processing of transparent materials. The material is removed with little energy coupled into the workpiece producing minimal collateral damage.

These lasers are especially attractive for processing of wide band dielectrics and very hard materials which are difficult to process with longer pulse lasers. Lasers do not exhibit tool wear and remain consistent throughout the entire machining process, motivating their use over mechanical alternatives [1-3]. Longer pulse width or CW lasers rely on slow thermal processes for material removal which may not be acceptable for the machining of sensitive or refractory materials. The chief drawback of laser machining is the lack of the intrinsic position control or feedback of the location of material removal; since the beam is not a physical object, its position is not precisely controlled by geometry like a cutting tool. Usually, its position is well known in the plane of the material surface, but the laser will ablate material to some a priori unknown depth, depending on process parameters and surface geometry. A mechanical tip only cuts when it is in contact with material, and so can machine flat or constant depth features more consistently than a laser.

Ultrashort pulsed lasers achieving high average power (5-50 W) have exhibit a wide range of applicability, coupled with increased throughput potential, and thus there is impetus to develop a quantitative model for material removal using these devices. This paper discusses the specifics of ultrashort pulse laser material removal in wideband dielectrics both by individual pulses and overlapping pulse trains. Experimental results are presented on machining of trenches in alumina, and a model for controlled pulse train machining is proposed. Finally, industrial considerations are discussed, with the emphasis on the optimization of the rate of material removal.

2. Experiment Method

2.1. Experiment

Concentric grooves were machined into an alumina disk to investigate the effects of pulse-to-pulse spacing, energy density (fluence), and overall dose. Figure 1 shows a characteristic sample of this work, and the second image shows an SEM micrograph of the alumina surface. There is minimal heat affected zone (no appreciable grain growth) and a lack of cracking and other undesirable structures that may adversely affect the mechanical properties of the material as the result of ablation.

An electric motor was used to spin the part at a specific angular velocity, in order to control the feed rate and pulse overlap. The laser was focused on the surface using a 30-cm planoconvex fused silica lens. This system produced 110-120 fs pulses at a repetition rate of 1-kHz and a wavelength centered at 825 nm. Pulse energies of several hundred microjoules were used for the machining and are reported in the results.

2.2. Modeling

Intense radiation due to an ultrashort laser pulse incident on the transparent dielectric generates free electrons through a combination of multi-photon ionization and electron avalanche. If the electron density is below a critical threshold, the free electrons do not substantially affect radiation propagation beyond the surface. When the electron density reaches the critical threshold at some point, strong absorption takes place. Therefore the ablation has a threshold fluence $F=F_c$ corresponding to the generation of a supercritical electron density layer. The evaluation of absorption at $F> F_c$ was presented recently [4]. It was shown that as fluence increases, the absorbed energy reaches a saturation level and the reflected energy increases linearly with incident fluence. As a result, one can expect this saturation effect to adversely affect the ablation rate, meaning that the ablation rate will be frustrated at fluences beyond the threshold.

We propose the following expression for maximum depth (d) of ablated material obtained in our experiments:

$$d = d_0 \ln \frac{F}{F_c} \qquad (1)$$

where d_0 is a scaling parameter.

Consider the shape of the crater produced by the single pulse with a Gaussian fluence profile

$$F = F_0 e^{-\frac{r^2}{a^2}} \qquad (2)$$

Using (2) and (1) we see that the crater has a parabolic shape:

$$d(r) = d_0(\ln\frac{F_o}{F_c} - \frac{r^2}{a^2}) \tag{3}$$

with ablation radius r_c, or the radius beyond which d=0:

$$r_c = a\sqrt{\ln\frac{F_0}{F_c}} \tag{4}$$

The volume of a crater V is:

$$V = \frac{\pi d_0 r_c^4}{2a^2} = (\ln\frac{F_0}{F_c})^2 \frac{\pi d_0 a^2}{2} \tag{5}$$

Consider now the trench produced by a train of pulses. We assume that there is no interaction between the pulses; a statement we must check against the experiment. The displacement between two sequential shots *b* can be related to the relative fluence of the n+1 pulse at the center location of the previous shot n, which is called the pulse overlap *f,* by the relation:

$$f = e^{-\frac{b^2}{a^2}} \tag{6}$$

The trench produced by a pulse train traversed across the surface at constant velocity is aligned along the x axis, with x=0 corresponding to the center of the first pulse. The fluence produced by the nth pulse at x=0 is:

$$F_{(x,y)} = F_0 \exp\left(\frac{(nb)^2}{a^2}\right)\exp\left(-\frac{y^2}{a^2}\right) \tag{7}$$

where y is the direction transverse to the trench direction. Let us assume that the redeposition of debris is not important and the removal rate is not affected by the interaction with previous pulses. The material removed by the nth pulse at x=0, d_n, is:

$$d_n = d_0\left[\ln\left(\frac{F_0}{F_c}\right) - \left(\frac{nb}{a}\right)^2 - \frac{y^2}{a^2}\right] \tag{8}$$

where the y dependence describes the transverse groove shape. The total material removal D at the origin is:

$$D = \sum_{-n_m}^{n_m} d_n \tag{9}$$

The summation is taken up to the ablation radius, or the last pulse to remove material from the origin

$$n_m = \frac{a}{b}\sqrt{\ln\frac{F_0}{F_c} - \frac{y^2}{a^2}} \tag{10}$$

Taking this into account we have

$$\sum_{-n}^{n} k^2 = \frac{n(n+1)(2n+1)}{3} \tag{11}$$

and

$$D = \sum_{-n_m}^{n_m} d_n = \frac{a^2}{b^2}\sum_{-n_m}^{n_m} d_o(n_m^2 - n^2) = \frac{b^2}{3a^2} d_0 n_m (4n_m^2 - 1)\,. \tag{12}$$

Substituting (10) into (12) the depth of the trench in cross-section is

$$D(y) = \frac{bd_0}{3a}\sqrt{\ln\left(\frac{F_0}{F_c}\right) - \frac{y^2}{a^2}}\left[\frac{4a^2}{b^2}\left(\ln\left(\frac{F_0}{F_c}\right) - \frac{y^2}{a^2}\right) - 1\right] \tag{13}$$

with the assumption that the displacement between shots is much less than the spot radius b<<a, the centerline depth (y=0) is

$$D(0) \approx \frac{4ad_0}{3b}\left(\ln\frac{F_0}{F_c}\right)^{3/2}\,. \tag{14}$$

3. Results

Grooves were laser machined in 99.6% dense alumina samples which had already been ground and polished on each surface. We used a Ti:Sapphire short-pulse laser with a pulse repetition frequency (P) of 1000 Hz, an average pulse width of 110 fs, and a maximum pulse energy of 1 mJ, resulting in a maximum average power of 1 W. Machining multiple circuits in the same trench results in a discrete and consistent depth increase, i.e. two coincident trenches result in one trench of twice the depth. This process linearity is important for the deterministic machining of surfaces.

Groove cutting experiments were performed at a number of beam energies to verify the groove depth logarithmic dependence on fluence. To this a curve of the form predicted from above is fit. The parameters d_0 and F_c are obtained from a best-fit of equation (14) to the experimental data using *Mathematica*. Figure 2 shows the groove depth data used for the parameter extraction. The best-fit curve in Figure 2 is that for the values d_0=0.31 μm, and F_c=0.69 J/cm^2 (peak fluence). A recent work in alumina using a 180 fs pulse width 775 nm laser at 1 kHz reported the threshold fluence to be 1.1 J/cm^2 [5]. The disagreement between the fluence thresholds in this work and Perrie et al. may be due to the substantially longer pulse duration in their work, as threshold fluence is expected to rise with increasing pulse width. Using the model developed in this work to fit the volume removal data reported in the aforementioned work results in an underestimate of ablation rates observed in this work.

Figure 3 shows an interferometric profile measurement of a groove, compared to the profile predicted according to the equations presented above. Both the groove width and depth are accurately predicted, as is the shape of the groove.

There is some roughness in the sample profile, and some of this can be expected. The material was not perfectly smooth before ablation and is not homogeneous; it is composed of consolidated particles. These particles may detach in whole or part or may ablate slightly differently depending on crystallographic orientation to the surface and the incident laser, instead of behaving as a homogeneous continuum.

3.1. Optimization

Now, consider a trench of profile given by (13). For a given process, the laser pulse has a maximum energy, but can be deposited in an area of arbitrary size, which is related to the parameter *a*. Reducing the incident area of the beam correspondingly increases F_0. However, we know that due to the logarithmic dependence of material removal on fluence, a saturation effect mitigates the benefits of highly focused beams. As the beam is widened the fluence decreases, and the characteristic width of the trench increases. We might expect therefore that due to the saturation effects discussed above, that spreading the beam over as large an area as possible, while keeping the fluence in the critical regime, is the most efficient use of energy for material removal. Here this is examined, and some volume removal rates are predicted.

The area of the trench is simply the integral of the depth, evaluated from $-r_c$ to r_c,

$$A = \int_{-r_c}^{r_c} \frac{bd_0}{3a}\sqrt{\ln\frac{F_0}{F_c} - \frac{y^2}{a^2}}\left(\frac{4a^2}{b^2}\left(\ln\frac{F_0}{F_c} - \frac{y^2}{a^2}\right) - 1\right)dy = \frac{d_0\pi}{6b}\ln\frac{F_0}{F_c}\left(3a^2\ln\frac{F_0}{F_c} - b^2\right) \quad (15)$$

and the volume removal rate is this area multiplied by the feed rate, or

$$\dot{V} = (P\cdot b)A = P\frac{d_0\pi}{6}\ln\frac{F_0}{F_c}\left(3a^2\ln\frac{F_0}{F_c} - b^2\right). \quad (16)$$

Here P- is laser repetition rate. Let us mention that for applicability of our model the number of shots observed in some point must be bigger then one. From (10) one can see that it means

$$\frac{a^2}{b^2}\ln\frac{F_0}{F_c} > 1 \tag{17}$$

and hence, (15) is always positive.

In experiments varying the pulse overlap *f*, it is seen that for *f*=0.8-0.9 that the bottom of the trench is essentially at a constant depth. For small *f*, the bottom of the trench can vary in depth due to local variations in dose. Thus *f* is important to the process quantitatively due to smoothness concerns. Through experimentation we found the minimum overlap which seemed to provide satisfactory groove geometry, and then fixed it at this value for the optimization. There are also results showing that high energy deposition rates on a given area may increase material redeposition and surface damage, further limiting the choice of *f* due to process quality concerns [5].

Consider a process using pulses of fixed energy $E_p = F_0 \pi a^2$, with the repetition rate P. We wish to find the beam diameter that makes the most effective use of the incident fluence, spread over the largest possible area. If *f* is held constant at 0.85 for groove quality, and assume E_p and P are the maximum available and fixed, and vary the beam width parameter *a*, the fluence F_0 is determined and a great deal of the process depends on this parameter. Thus, the radius of the beam is the control input, F_0 the output, and the other parameters *f,* E_p, and P are fixed. This does not mean that feed rate is constant, but in fact as *a* increases with constant *f*, the feed rate must also accordingly increase.

Using substitutions from (6) and (7), and eliminating *a,* we have the equation for volume removal rate as a function of F_0,

$$\dot{V} = P\frac{d_0}{6F_0}E_p \ln\frac{F_0}{F_c}\left(3\ln\frac{F_0}{F_c} + \ln f\right) \tag{18}$$

where the pulse energy E_p and *f* are held constant.

The volume removal rate shown in Figure 4 has a maximum at F_0=5.23 J/cm^2, which is 7.6F_c. This condition corresponds to the optimal beam radius, and is relatively constant for various pulse overlaps. Beams with smaller radius have excessive fluence for which ablation is not efficient. Beams with larger radius have low ablation efficiency due to the low fluence. The sensitivity of volume removal on fluence is qualitatively evident in the groove depth data in Figure 2, where the logarithmic curve rises quickly initially, and then more slowly at higher fluence. Given the leisurely initial descent of the curve in Figure 4, however, there is considerable leeway in the choice of incident fluence, while maintaining near optimal machining. In this case, any peak fluence from 3.5 to 8.5 J/cm^2 yields >95% of the optimal removal rate. In practice the volume removal rate can be considered essentially linearly dependent on fluence in the increasing region and invariant over the near optimal region. The wide near-optimal band makes the process forgiving to changes in parameters resulting from application specific problems, such as feed rate limitations.

The above results were obtained for the fixed pulse energy. In another study[5], the beam radius was kept fixed but the pulse energy was increased. In this case one can see that the removed volume will grow continuously with fluence, consistent with experiment [5]. If one will consider the removal efficiency, the ratio of removed volume to pulse energy, this quantity as function of fluence will have the same shape as (18) with the same optimal fluence**.**

4. Conclusion

We demonstrated that ultrashort laser pulses are able to produce high quality trenches on an alumina sample. These trenches have a good quality and the grooves' shape, depth, and width are in agreement with the prediction of a simple model. The results of the paper show the process to be predictable and amenable to processing constraints. The proposed model predicts a wide range of fluences for which an ultrashort laser can operate at near optimal capacity. These results indicate the possibility of using such a process to machine arbitrary 3-dimensional surface profiles into hard dielectrics such as alumina, with a high degree of precision and efficiency.

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5. References

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List of Figures

Figure 1. SEM micrographs of machined alumina surfaces. Left shows 3 grooves machined at different laser conditions for comparison. Higher magnification show that the ablated surface has similar surface characteristics as that of material which has not been ablated.

Figure 2. Groove depth data taken for f=0.85 in alumina, with multiple pass depth normalized to compare to depth from a single pass. This data is used to extract the single shot parameters d_0 and F_c. The logarithmic dependence of depth on fluence is evident.

Figure 3. Groove cross-section and prediction for F_0=37 J/cm^2, with F_c, d_0 derived from the groove depth data in Figure 2. The measured cross-section is taken from an interferometric scan of a three-pass groove. The roughness seen in the figure is typical.

Figure 4. Volume removal rate (mm^3/s) as a function of F_0 (J/cm^2), from Equation (18). The optimal fluence lies between 3.5 and 8.5 J/cm^2 peak fluence for alumina. The optimal removal rate is proportional to laser power. For the 1W employed here, the optimal removal rate is 0.012 mm^3/s.

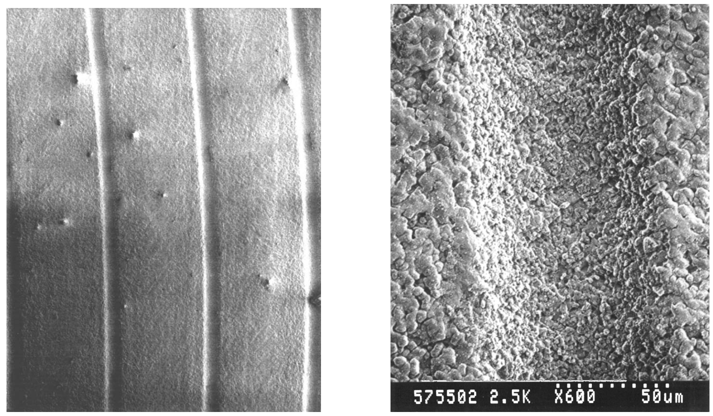


Figure 1

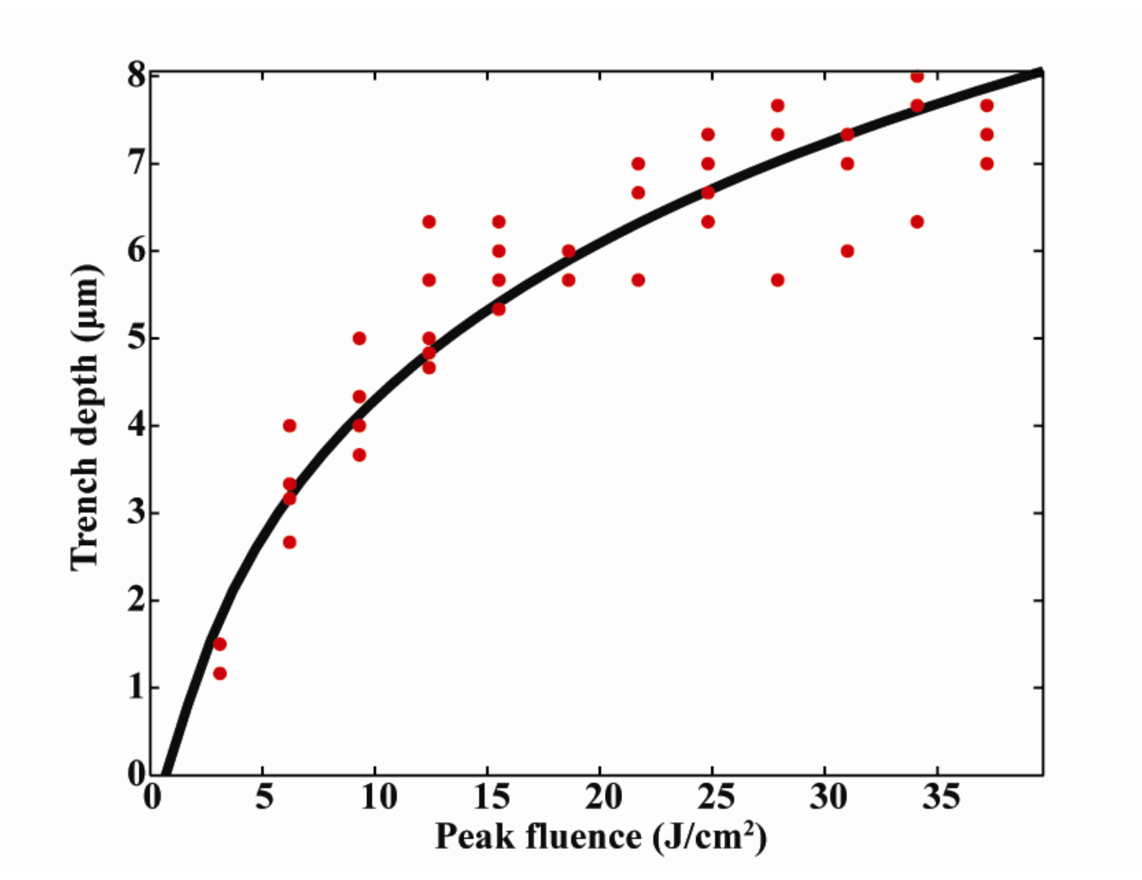
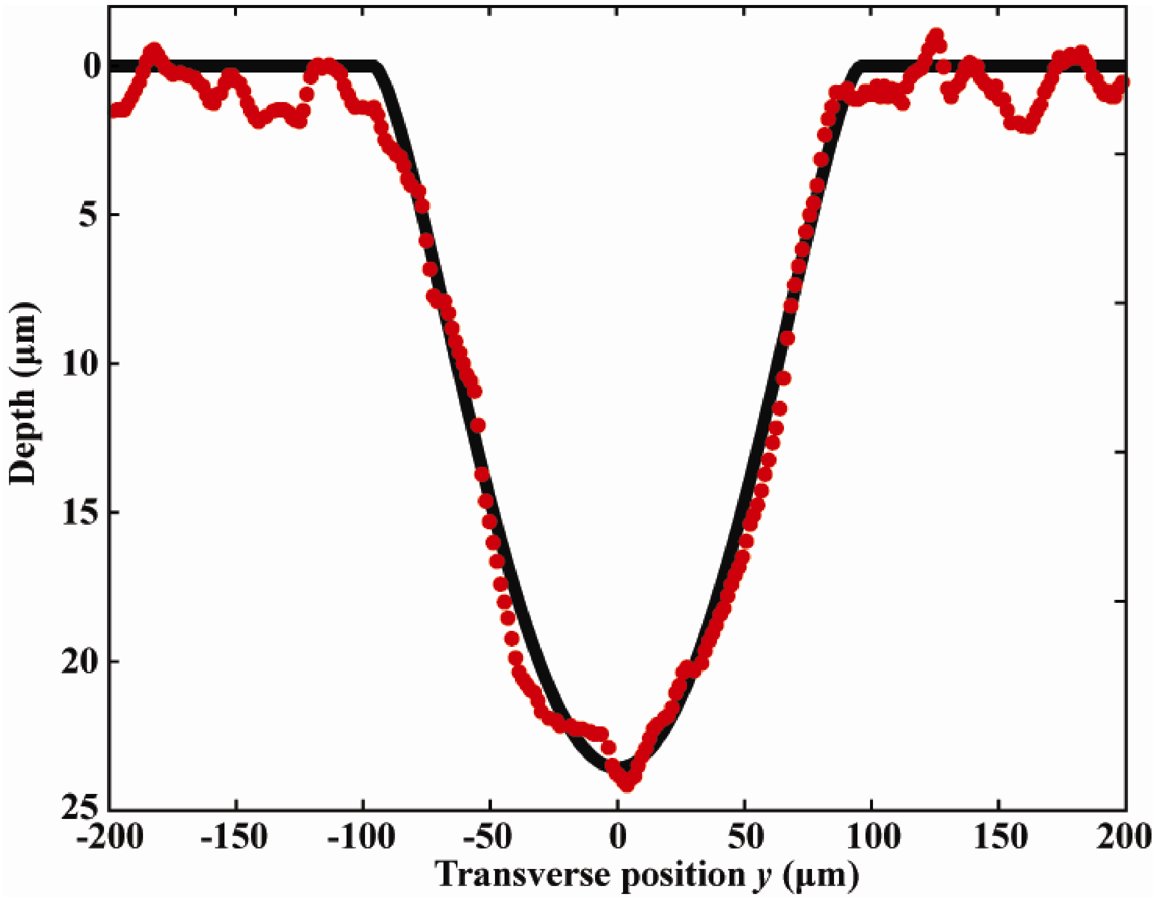


Figure 2



Depth (μm)
0
5
10
15
20
25
-200
-150
-100
-50
0
50
100
150
200
Transverse position y (μm)

Figure 3

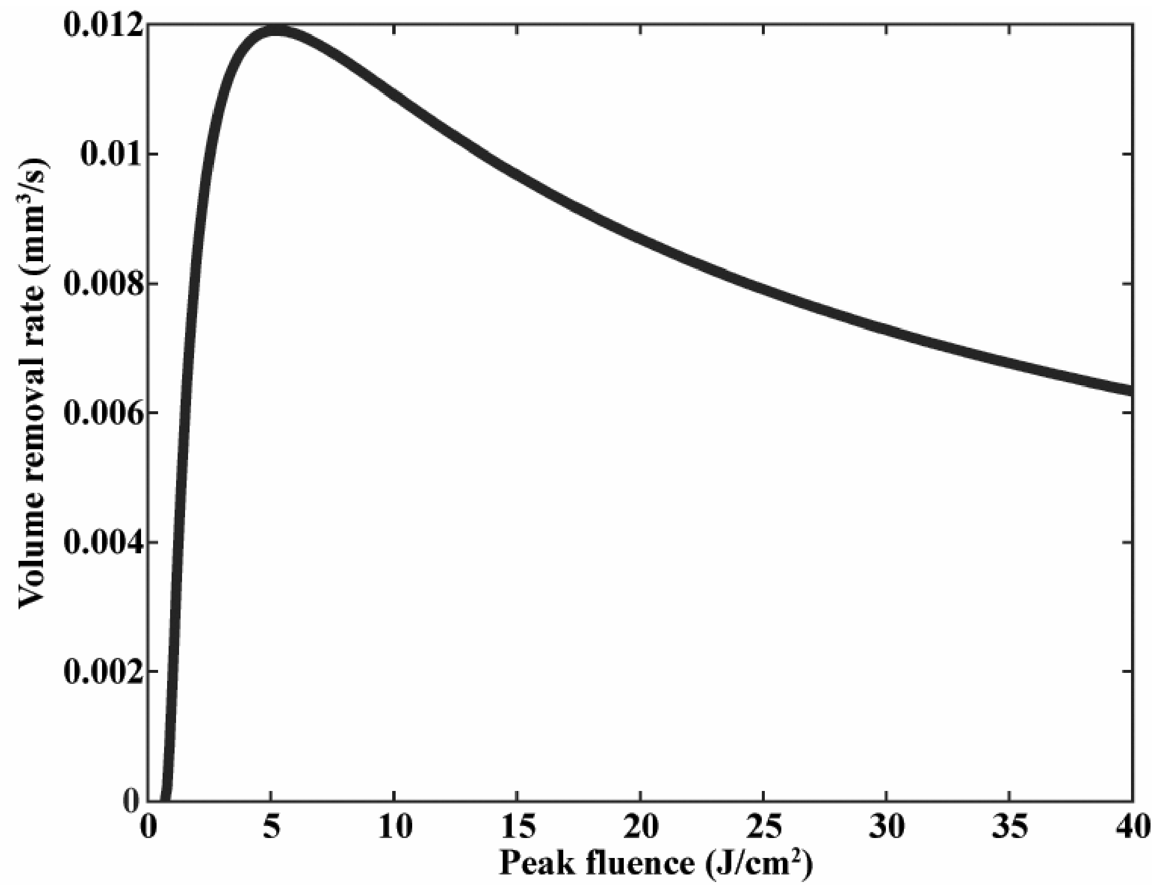

0.012
0.01
0.008
0.006
0.004
0.002
0
Volume removal rate (mm³/s)
0
5
10
15
20
25
30
35
40
Peak fluence (J/cm²)

Figure 4