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LLNL-JRNL-480645

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D. A. Cross, C. W. Carr

April 19, 2011

Applied Optics

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David A. Cross and Christopher W. Carr*

Lawrence Livermore National Laboratory,

7000 East Avenue, Mail Stop L-592, Livermore, CA 94550

**Corresponding author: carr19@llnl.gov*

Abstract

The influence of laser parameters on laser-induced damage in the bulk of KDP is difficult to determine because the damage manifests as discrete sites a few microns in diameter distributed throughout a relatively large volume of material. Here, we present a method to directly measure the size and location of many thousands of such sites and correlate them to the laser conditions which produced them. This technique is used to characterize the effects of pulse duration on damage initiated by 1053 nm light in the bulk of KDP crystals. We find that the density of damage sites produced by 1053 nm light is less sensitive to pulse duration than was previously reported for 526 nm and 351 nm light. In addition, the effect of pulse duration on the size of the damage sites produced appears insensitive to wavelength.

OCIS codes: 140.3330, 140.3380, 140.3440, 140.3515, 140.3538

Introduction

Potassium Dihydrogen Phosphate (KDP) is especially well suited for use in large-aperture lasers systems due to the ability to grow single crystals to a large size (~300 kg) with growth rates exceeding 10 mm per day. As is the case with all laser materials, KDP is susceptible to laser-induced damage. In KDP, damage typically manifests as discrete localized micro-cavities in the bulk of the material [1,2]. These micro-cavities, commonly referred to as pinpoints, have a complex morphology composed of a cavity which shows evidence of melting and re-crystallization surrounded by more subtly modified outer regions [1,3]. Although each pinpoint scatters very little light individually, in large numbers these pinpoints can be detrimental because of the collective effect of increased beam contrast. The number of pinpoints which can be tolerated depend on the size and density of sites as well as the spatial variation requirement of the final laser beam. It is therefore desirable to have a good understanding of how laser parameters affect both the size and density of damage.

Previous damage initiation experiments have been conducted with a variety of pulse shapes and wavelengths using sub-millimeter beam diameters [4-7]. These experiments commonly referred to as S/1 and R/1 tests result in curves depicting the probability of initiating at least one damage site as a function of fluence. While such measurements are capable of producing excellent qualitative results, the absolute Laser Induced Damage Thresholds (LIDT) tend to be higher than those found with large-beam damage density measurement experiments. This discrepancy is primarily due to the inherent statistical limitations associated with sampling volumes which are small compared to precursor densities [8,9]. Density is also a preferable measurement of damage because it can be scaled to larger areas easily.

For pinpoints induced in KDP by 351 nm (3ω) light, size and density have been shown to depend on laser parameters such as pulse duration, pulse shape, and fluence [3,10-12]. Both pinpoint size and density have been shown to depend strongly on pulse duration [13]. It has also been shown previously that the LIDT in KDP can depend significantly on the direction of laser propagation and thus the angle of crystal cut [14]. The pinpoint density as a function of fluence $\rho(\phi_1)$ measured for a single pulse duration (τ_1) may be used to estimate the damage produced by another pulse duration (τ_2) according to

$$\rho(\phi;\tau_2) = \rho\left(\phi \times \left(\tau_1/\tau_2\right)^{\gamma};\tau_1\right) \quad (1)$$

where γ the pulse scaling constant [13,15]. Previously, pulse scaling for 3ω and 2ω (527 nm) light has been investigated [15,16]. In this work we investigate the effect of pulse duration of 1053 nm (1ω) laser pulses on both pinpoint density and size.

While a direct measurement of damage density and subsequent correlation to local fluence is generally recognized as ideal, these damage sites are difficult to measure due to their large numbers, small sizes, and the relatively large volume of material in which they occur. In the past, these difficulties have been circumvented by one of several methods. For example, the need to locate or count any pinpoints can be eliminated by measuring the amount of light they scatter in a side illuminated geometry [17]. The amount of scattered light from a damage site is assumed to be proportional to damage site density and size, however as stated previously damage site morphology is complex thus making a connection to light scatter complicated and difficult to determine without detailed structural information for each site. A second approach has been used that eliminates the difficulties in a three dimensional measurement by sampling the damage density in one or more widely separated two dimensional x-y regions. A short-depth of focus microscope is used to count all the individual damage initiations in a thin layer and then extrapolating to the three dimensional volume. Conversely damage initiations have been counted in the bulk by using a large-depth of focus objective and integrating through the thickness of the sample [18]. While the former method is capable of distinguishing site sizes and sampling variations in damage density associated with z, it tends to undercount small sites relative to large ones because larger sites exhibit a larger fracture zone surrounding the site leading to greater light scatter. The latter technique will correctly find all damage sites, but does not preserve size or depth information. Damage site size may be important when using a two dimensional scan as larger sites may be over-counted by appearing to be in the scanned region when they are not. Damage site depth is highly relevant for KDP since it is often used for harmonic conversion, and thus the damage behavior will vary with the increasing harmonic power through the crystal. [19]. In this work we demonstrate the use of a microscope-based technique to obtain damage density measurements without any of the aforementioned shortcomings.

Experiment

The experimental setup for initiating the damage in the KDP is described in detail elsewhere [20]. Briefly, two 5 cm x 5 cm x 1 cm crystals were tested with 1053 nm light, in temporally Gaussian pulses with a variety of FWHM durations. Each test was conducted on a volume of crystal (sub-aperture) not previously exposed to laser irradiation. Two sub-apertures on the first sample, a Z-cut KDP crystal (cut normal to the crystal z axis), were irradiated with pulses of duration 3.5 ns and 10 ns, respectively. Three sub-apertures on a second doubler-cut (cut at ~41^{o} from normal to crystal z axis) sample were irradiated with 1 ns, 3 ns and 10 ns duration pulses, respectively. The laser spot size is on the order of 1cm diameter and the fluence varies by +/- 20% over the beam area.

Measurement

The measurement technique reported here is similar to those used previously [8] in that we collect damage site information using automated white light microscopy. However here we extend this technique from a surface to a volume measurement. The measurement consisted of scanning the entire laser initiated volume using polarized bright field illumination and a 10X Mitutoyo long working distance microscope objective with a numerical aperture of 0.28. A polarizer in front of the objective removed double counting of pinpoints due to the birefringence in the doubler-cut KDP. This optical system resulted in an x-y field of view of ~0.02mm^2 and a depth of focus of 10μm with a system resolution of 200nm/pixel. In order to measure the entire ~ 1cm^3 volume in z-steps of 10μm, a total of approximately 5 million frames were examined. Identifying and measuring individual damage sites from a set of micrographs is a simple task for a person, however examining the ~10^6 frames manually would be a daunting task, so an automated process was devised. Each frame was analyzed in situ by thresholding and outputting the x,y,z position and area of the identified dark regions. The threshold level necessary to detect the smallest sites, results in multiple detections of larger sites, which will be discussed below.

Analysis

By comparing the automated detections to manual detections on a control sample, we know that greater than 80% of the automated detections are non-unique. A typical separation between unique sites can then be calculated from the volume scanned and the mean Euclidean distance between detections. To remove spurious detections but not the unique sites we first remove cracks based on proximity, keeping the largest as real. We then remove multiple counts of sites caused by the same site being detected at more than one z step as seen in figure 1.

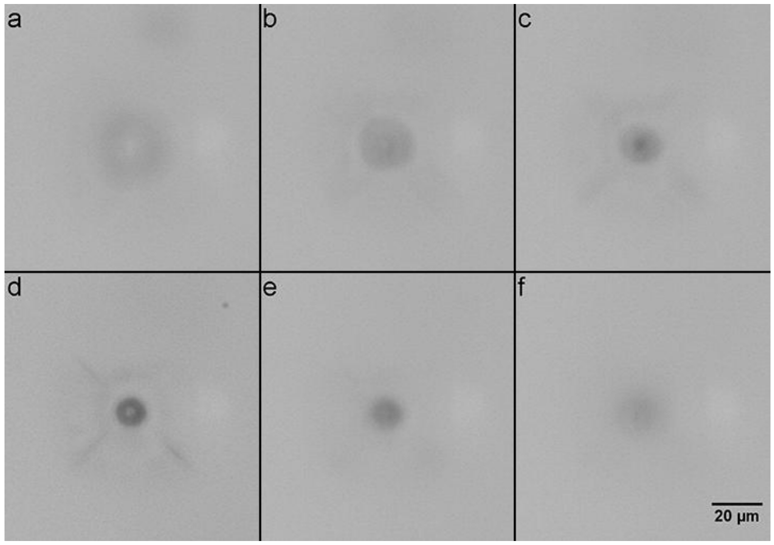

Figure 1 Representative example of a damage site in the bulk of the KDP sample imaged at six different focus positions in steps of 10µm. Note that although the correct depth is in step d, the site is detected in many other steps. Also note the small secondary damage site in step d is only seen in this step.

This removal is accomplished by examining sites which are detected at the same x,y location in sequential z steps. The site in the middle of the detection range is kept. The full algorithm is shown in detail in figure 2.

```
detectionList = Array[x,y,z,size];
siteList = Array[empty];
roi = x,y radius from average separation, any z;
detectionList.sort(size largest to smallest);

while(detectionList.hasMoreElements)
        tempList=Array[empty];
        currentDetection=detectionList.firstElement;
        define roi around currentSite;
        for(each remaing element in detectionList)
                if(detectionList.element exits in roi)
                        add element to tempList;
                        remove element from detectionList;
        split(tempList into segments by contiguous detections in z);
        for(each segment)
                for(each z-step in segment)
                        delete all except largest detection;
                true coordinate = centroid x,y,z;
                add site to siteList;
Output siteList;
```

Figure 2 The algorithm used to determine the actual number and location of damage sites from a large detection list.

The accuracy of this algorithm was evaluated by manually measuring 50 representative sites chosen at random from the data set. A comparison of the site classification (either damage site or superfluous detection) and the damage site positions between the manual measurements and the automatic detection algorithm resulted in an algorithmic accuracy of greater than 98%.

Once the microscopy data is reduced to only unique sites, the effect of laser parameters on their production can be considered. The fluence profile is registered to the damage using corresponding local fluctuations in the fluence and the damage density and then assigning fluence to each individual damage site as described previously [8]. Pinpoint density plotted as a function of fluence ($\rho(\phi)$) for the doubler-cut sample and Z-cut sample is shown in figure 3 and its inset, respectively. Average pinpoint core radius for the doubler-cut sample plotted as a function of fluence ($a(\phi)$) is depicted in Figure 4. The $\rho(\phi)$ and $a(\phi)$ data are fit to allometric and linear relationships, respectively.

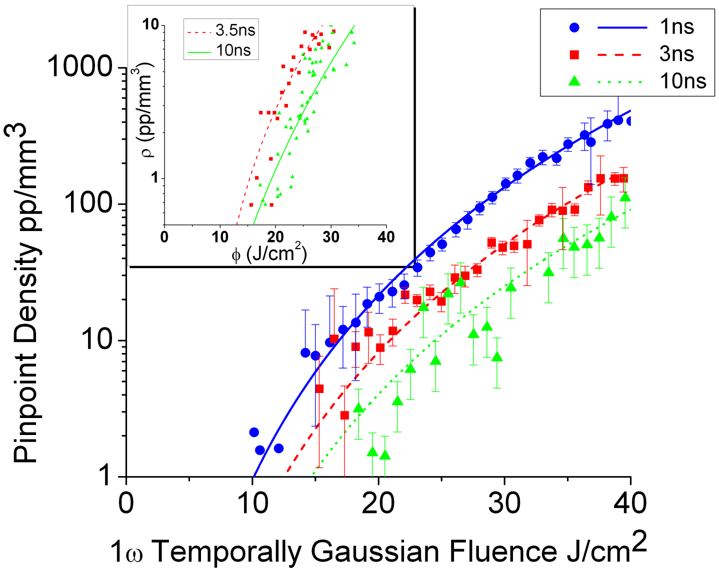

Figure 3 Local damage density plotted vs. local fluence of 1ω temporally Gaussian pulses with durations of 1 ns, 3 ns, and 10 ns, respectively. Allometric fits to the data are also shown. The ρ(ϕ) (pinpoint density as a function of 1ω temporally Gaussian fluence) data for damage caused by pulse durations of 3.5 ns and 10 ns on the Z-cut sample are shown in the inset.

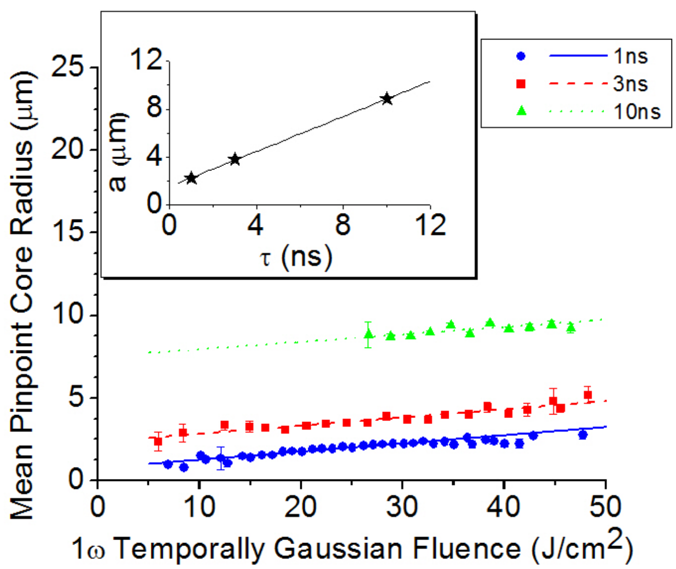

Figure 4 Local pinpoint radius plotted vs. local fluence caused by 1ω temporally Gaussian pulses of 1 ns, 3 ns, and 10ns duration. Linear fits to the data are also shown. Inset: Mean pinpoint core radius (a) vs. pulse duration (τ) at a fluence level of 30 J/cm^2.

The pulse scaling constant γ in equation 1 was obtained by comparing the $\rho(\phi)$ produced by the different pulse durations within the same sample: 3.5 ns and 10 ns pulse duration for Z-cut sample and 1ns, 3 ns and 10 ns pulse duration for doubler-cut sample. Data sets were not compared between samples because of known sample variability. Each of the five $\rho(\phi)$ data sets was first fit to an allometric function of the form

$$\rho(\phi;\tau_1) = A\phi^b \tag{2}$$

where A and b are fitting parameters for a given pulse duration. Next, each $\rho(\phi)$ data set is fit to equation 3

$$\rho(\phi;\tau_2) = A\left(\phi \times \left(\tau_1/\tau_2\right)^\gamma\right)^b \tag{3}$$

with A and b given by the constants obtained from equation 2; τ_1 and τ_2 are the pulse durations. This least squares fit has only γ as a fitting parameter. The scaling factor γ was calculated at fixed densities of 10, 50, and 100 pp/mm^3 and as expected, the value of γ was found to be the same within 0.5%. The average γ for 1ω light was found to be $\gamma = 0.17 \pm 0.03$.

This result contrasts with previously reported results for 2ω and 3ω pulses of durations between 1 ns and 10 ns, where the pulse scaling constant is approximately 0.3 and 0.4 for 2ω and 3ω, respectively [16,21]. This difference suggests that the density of damage initiated with 1ω light is much less sensitive to pulse duration than is the case for 2ω and 3ω light [15,21]. In addition we found that damage site diameter increased roughly linearly with fluence for 1ω light. This behavior *is* similar to that observed with Gaussian pulses of both 2ω and 3ω light [15,17].

Discussion

In this work we have demonstrated that for 1ω Gaussian pulses of 1 ns, 3 ns and 10 ns duration, the dimension of damage sites in the bulk of KDP varies approximately linearly with fluence. Furthermore the slope of the best fit size vs. fluence line is (within the uncertainty of the measurements) the same for all pulse durations. At a given fluence the size of the pinpoints is also seen to increase roughly linearly with pulse duration for pulse durations in the range of 1 ns to 10 ns. This is consistent with previous results which showed that for 3ω light the average pinpoint size varied linearly with pulse duration for durations between 1 ns and 20 ns [15].

Previous work on pulse scaling at 2ω and 3ω has shown that pulse scaling is valid even in samples that display very different damage thresholds [15,16]. Here we have shown that though the crystal cut changes the damage threshold, relative pulse scaling for 1ω is constant. It has been previously reported that for 3ω Gaussian pulses, pinpoints increase linearly in size with fluence [17,19,22]. In this work we also see a roughly linear relationship between pinpoint size and fluence, albeit far weaker.

The dependence of size and density on pulse duration and fluence presented here may be useful in predicting the lifetime and operational limits of KDP optics used at 1ω because the total bulk damage can be estimated for arbitrary pulse durations and fluences. The data may also suggest a technique for extending the useful range for these materials. By intentionally initiating damage with short pulse durations at or above the target fluence, an equal density of sites will be created, however the damage sites will be significantly smaller and thus the total damaged volume will also be less.

Acknowledgement

This work was performed under the auspices of the U.S. Department of Energy (DOE) by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

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