UCRL-JRNL-214793

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

The effect of multiple wavelengths on Laser-induced damage in DKDP crystals

C. W. Carr, J. M. Auerbach

August 24, 2005

Optics Letters

The effect of multiple wavelengths on laser-induced damage in DKDP crystals

C.W. Carr and J.M. Auerbach
University of California
Lawrence Livermore National Laboratory
7000 East Avenue, mail stop L-592
Livermore, CA 94550

Laser-induced damage is a key factor that constrains how optical materials are used in high-power laser systems. In this work the size and density of bulk laser-induced damage sites formed during frequency tripling in a DKDP crystal are studied. The characteristics of the damage sites formed during tripling, where 1053-nm, 526-nm, and 351-nm light is simultaneously present, are compared to damage sites formed by 351-nm light alone. The fluence of each wavelength is calculated as a function of depth with a full 4D(x,y,z,t) frequency conversion code and compared to measured damage density and size distributions. The density of damage is found be predominantly governed by 351-nm light with some lesser, though non-negligible contribution from 526-nm light. The morphology of the damage sites, however, is seen to be relatively insensitive to wavelength and depend only on total fluence of all wavelengths present.

Potassium dihydrogen phosphate and its duterated analogs ($KH_{(2-x)}D_xPO_4$) are used in both tabletop and large-aperture lasers in frequency converters. In order to produce UV light with Nd:glass lasers the fundamental wavelength of 1053 nm (1ω) is first ‘doubled’ with a KDP second harmonic generator (SHG) to 526-nm (2ω) light. The production of 351-nm (3ω) light, or ‘tripling’, is achieved by mixing the 2ω light with residual 1ω light in a DKDP third harmonic generator (THG). This non-linear mixing take place through the depth of the crystal and hence results in varying amounts of each wavelength being present as a function of depth. The intensities required for efficient frequency conversion can be large enough to damage the crystals.[1-3]

Laser-induced damage in (D)KDP manifests as localized micro-cavities in the bulk of the material. These micro-cavities are commonly referred to as pinpoint damage sites or simply pinpoints (pp). The size and density of the pinpoints is highly dependent on such laser parameters as fluence, pulse duration and wavelength.[2, 4] Bulk damage in (D)KDP optics is undesirable because at sufficient densities (~10 pp/mm^3) scatter from pinpoints causes down stream spatial intensity modulations (contrast) which may in turn damage other optics.

Historically only the shortest wavelength present during frequency conversion (2ω or 3ω for SHGs and THGs, respectively) was regarded as a source of damage to the crystal. Single wavelength ‘damage probability measurements’ are still widely used to assess materials resistance to laser-induced damage (see reference 3 and references therein). While these types of measurements efficiently produce a qualitative measure of damage resistance they are not ideal for materials used in frequency conversation because of the multiple wavelengths inherently present. In addition, probability measurements determine the likelihood of one *or more* damage sites occurring in a fixed volume but not the number of sites. Because the number of sites that damage at a given fluence will increase with the volume of material exposed to the laser, damage probability measurements made in small test optics are not scalable to larger optics.

Recently the shortcomings of damage probability measurements have been partially addressed by measuring the damage density as a function of laser fluence ($\rho(\phi)$) for a single wavelength.[2] Although the $\rho(\phi)$ measurement is scalable, both the density and the morphology of the damage sites must be known to predict the amount of light scattered by damage.

In this work we consider for the first time the effect of multiple wavelengths on damage density and damage morphology in a tripling DKDP crystal and argue that 2ω, but not 1ω light, contributes to damage density. In addition, we show that the size of damage sites depends linearly on fluence, independent of wavelength.

Two tripler-cut samples from the same conventionally grown DKDP boule were damage tested in the Optical Science Laser facility[5]. The first was tested during frequency conversion (i.e. 1ω and 2ω light were mixed to produce 3ω light). The second sample was tested with 3ω light only. The two samples will henceforth be referred to as the converting and 3ω only samples, respectively.

The damage testing technique is described in detail elsewhere.[2] In brief the 3ω only sample and the converting sample were exposed to single 3-ns Gaussian FWHM laser pulses of ~ 8 J/cm^2 (3ω) and ~10 J/cm^2 (total fluence), respectively. The input fluence to the converting sample is a mixture of 1ω and 2ω light (see Figure 1), but the peak 3ω fluence is close to the 8 J/cm^2 seen throughout the 3ω only sample.

The fluences of the 1ω, 2ω, and 3ω light were calculated at 1 mm increments through the depth of the converting sample and may also be seen if Figure 1. The measured input 1ω near-field fluence distribution and temporal intensity profile were used to create a temporal and spatial varying field distribution and input to a full 4D(x,y,z,t) frequency conversion code[6]. The 3ω and 1ω and 2ω residual fields are calculated separately at each location along the depth of the converting sample. The calculated fields at the output face of the sample are compared to the measured values.

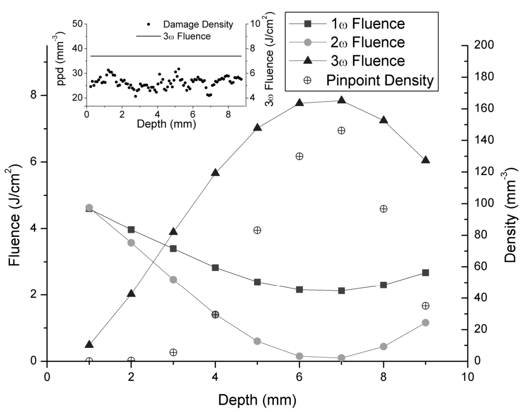

Figure 1. Damage density (pinpoints per mm^3) and 1ω, 2ω, and 3ω fluence as a function of depth a converting tripler. The inset shows the damage density and 3ω fluence (of 7.8 J/cm^2) as a function of depth for a subsection of the beam in a crystal exposed only to 3ω light.

The modeling[7] of the frequency conversion includes several physical processes: 3-wave mixing, 2 photon absorption, diffraction, non-linear susceptibility bulk loss, and walk off. Optical properties of the converting sample are specified by its material, thickness, cut, detuning angle, and optical aberrations. The converter used for these measurements consisted of a 11 mm thick Type I KDP doubler followed by a 9 mm thick Type II DKDP tripler. The model predicted that the averaged 3ω fluence reached a maximum not at the output of the tripler but at a distance of approximately 7 mm from the tripler entrance after which back conversion was predicted to occur. Conversely, for the 3ω only sample the fluence varied laterally across the beam but is constant throughout the depth, as may be seen in the Figure 1 inset.

The size and locations of the individual bulk damage sites produced by the laser are measured with an automated microscope as described else where.[2] The damage density as a function of z position in the converting sample and the 3ω only sample can be seen in figure 1 and its inset, respectively. Because the fluence in the 3ω only sample is not changing with depth the ~10% variations observed in the damage density are attributed to small-scale material inhomogeneties.

For the 3ω only sample variation in fluence (and hence) damage density is achieved by using a 15 mm diameter beam in which the fluence fluctuates laterally[2]. In the converting sample however, the fluence level of each wavelength changes as a function of depth although the total fluence remains relatively constant. The peak in 3ω fluence in the converting sample is at a depth of approximately 7 mm because of the back conversion taking place in the last 2 mm of the crystal. The damage density in the crystal also varies with depth and appears to be roughly correlated to the level of 3ω fluence. In Figure 2 the damage densities from Figure 1 are reploted against the local fluences present at each depth. The damage in the 3ω only sample is also shown as a function of fluence.

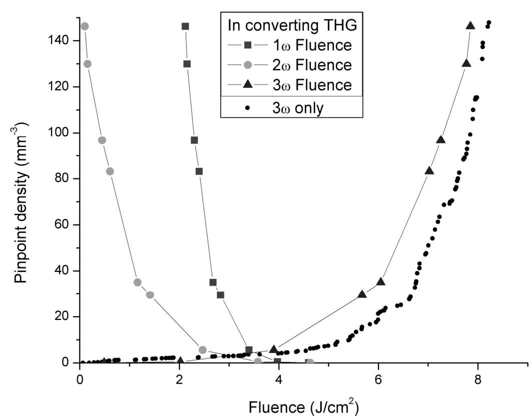

Figure 2. Damage density as a function of local fluence in a converting tripler and a crystal exposed to 3ω light only.

In figure 3 the size of the pinpoints in both the 3ω only and converting sample are also plotted as a function of local 1ω, 2ω, 3ω, fluence. In addition the pinpoint sizes from the converting sample are also plotted vs the sum of all local fluences.

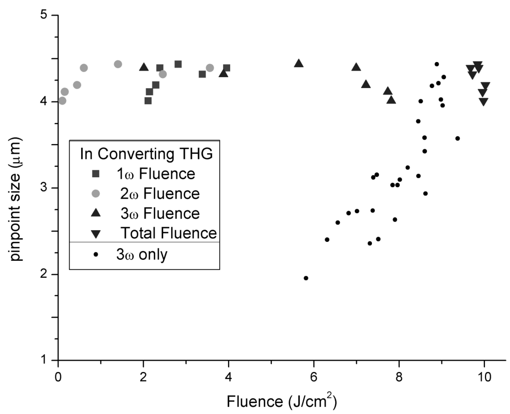

Figure 3. Pinpoint size vs fluence for the individual wavelengths and their sums in the converting THG and for the 3ω only experiment. The data from the surface is omitted to avoid inclusion of surface damage.

By comparing the pinpoint size and density observed as a function of the local fluence in the converting sample to that observed in the 3ω only sample, the relative importance of each wavelength on both aspects of damage initiation is revealed. The reduction of damage density with increased fluence observed for both 1ω and 2ω light in figure 2 confirms the long-held belief that neither of these wavelengths are the predominate source of damage. However the damage density as a function of local 3ω fluence does not match that observed in the 3ω only experiment indicating a contribution to the damage density of at least one of the other wavelengths.

Figure 1 shows that at a depth of 7 mm in the converting sample that there is ~ 8 J/cm^2 of 3ω, 2 J/cm^2 of 1ω and very little 2ω light present. The representation of this data in figure 2 indicates that the damage densities resulting from 8 J/cm^2 of 3ω light are similar in the 3ω only and converting experiments. This suggests that the 2 J/cm^2 of 1ω light did not add significantly to the damage density and that the general enhancement to the damage density in the converting sample is due to the presence of the 2ω light.

The negligible and week contribution to damage density by the 1ω and 2ω light, respectively, is in contrast to both wavelengths contribution to pinpoint size. Figure 3 indicates that in the 3ω only sample pinpoint size varies roughly linearly with 3ω fluence. In the converting sample, however, pinpoint size is constant, indicating that pinpoint size depends on total fluence not the local individual 1ω, 2ω, or 3ω fluence. It should be noted that for the 3ω only sample the 3ω fluence is also the total fluence. We see also that the pinpoint size as a function of total fluence is in relatively good agreement to the results from the 3ω only experiment.

In conclusion we have performed the first quantitative measurement of the effect of multiple wavelengths on both the damage density and pinpoint size in DKDP crystals. We have confirmed the that 3ω light is the dominate wavelength in producing bulk laser-induced damage in DKDP crystals, but that even small amounts of 2ω light simultaneously present produces a measurable increase in the damage density. The 1ω light does not appear to contribute to the density of damage.

In contrast, the size of the damage sites appear insensitive to the relative amounts of the various wavelengths but varies linearly with total fluence. This dichotomy in the wavelength dependence suggests that multiple energy absorption mechanisms are responsible for damage density and pinpoint size in DKDP crystals. We postulate that an initial absorption mechanism governs the density of damage sites. The strong dependence on wavelength of the supposed initial absorption mechanism appears consistent with earlier reports of a defect-assisted multi-photon absorption[8]. The insensitivity of pinpoint size to wavelength suggests that after the initial deposition of energy a wavelength independent absorption mechanism becomes dominate.

This work was performed under the auspice of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

1. P.P. DeMange, et al., Review of Scientific Instruments **75**, 3298 (2004).
2. C. W. Carr, et al., Review of Scientific Instruments **Submitted** (2005).
3. A. K. Burnham, et al., Applied Optics **42**, 5483 (2003).
4. J. J. Adams, et al., SPIE (2004).
5. M. Runkel, et al., BDS 2000 (2000).
6. J. M. Auerbach, et al., Applied Optics **40**, 1404 (2001).
7. D. Eimerl, et al., J. Mod. Opt. **42**, 1037 (1995).
8. C. W. Carr, et al., Physical Review Letters **91**, 127402 (2003).