LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-PROC-216742

Growth of Laser Damage in SiO2 under Multiple Wavelength Irradiation

M. A. Norton, E. E. Donohue, M. D. Feit, R. P. Hackel, W. G. Hollingsworth, A, M. Rubenchik, M. L. Spaeth

November 1, 2005

Boulder Damage Symposium XXXVII
Boulder, CO, United States
September 19, 2005 through September 21, 2005

Growth of Laser Damage in SiO_2 under Multiple Wavelength Irradiation

Mary A. Norton, Eugene E. Donohue, Michael D. Feit, Richard P. Hackel, William G. Hollingsworth, Alexander M. Rubenchik and Mary L. Spaeth

Lawrence Livermore National Laboratory, M/S L4592, PO Box 5508, Livermore, CA 94551

ABSTRACT

In laser systems using frequency conversion, multiple wavelengths will be present on optical components. We have investigated the growth of laser initiated damage in fused silica in the presence of multiple wavelengths. In particular, we measured growth at 351 nm in the presence of 1053 nm near the threshold of growth for 351 nm alone. The data shows that the sum fluence determines the onset of growth as well as the growth rate. The measured growth coefficient is consistent with all the energy being delivered at 351 nm. Additionally, we measured growth at 527 nm in the presence of 1053 nm near the threshold of growth at 527 nm alone. In this case, the sum fluence also determines the growth coefficient but the rate is consistent with all the energy being delivered at 1053 nm. We present the measurements and discuss possible reasons for the behavior.
.

Keywords: Laser damage, laser damage growth, laser damage growth threshold, UV fused silica.

1. INTRODUCTION

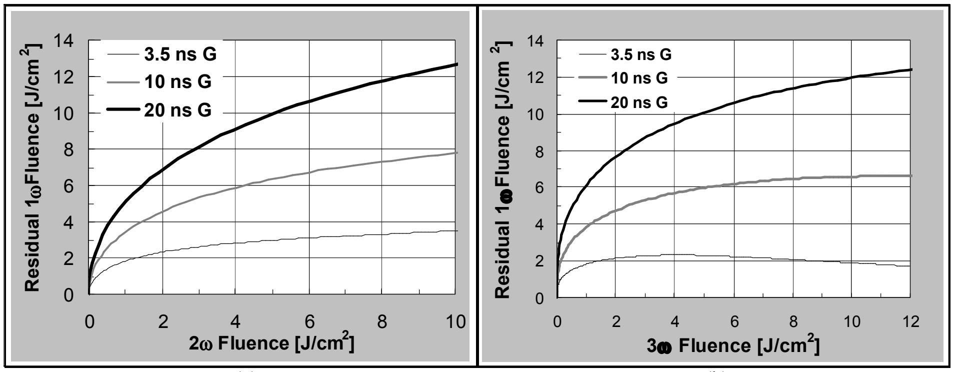
1.1 General

Laser systems that use frequency conversion to produce new wavelengths will have optical components with multiple wavelengths present. The lifetime of optics used in laser applications is limited both by laser-initiated damage and by the subsequent growth of the laser-initiated damage. Frequently, it is the growth of laser damage that determines the true operating costs of laser systems, since a damage site that does not grow or grows very slowly will not impede laser operation. Moreover, both laser damage initiation and laser damage growth on the optical exit surfaces dominate the damage events. Previous measurements of laser growth of laser damage sites on the exit surface of fused silica have been obtained at a single wavelength. [1,2,3]

This work focuses on the growth of damage after laser initiation under the simultaneous presence of two wavelengths. In particular, two conditions have been considered. The first condition is growth in the presence of the fundamental wavelength (1ω) and the frequency tripled wavelength (3ω). These are the two wavelengths that predominate in well designed frequency tripled systems. The second condition is growth in the presence of 1ω and the frequency doubled wavelength (2ω). These are the only two wavelengths in frequency doubled systems. In both sets of experiments the effect of the unconverted wavelength on both growth rate and threshold for growth will be explored.

1.2 Background

Our previous measurements of growth of laser damage at the second and third harmonics of a 1 μm laser system found a growth threshold of ~5 J/cm^2 for the third harmonic and a growth threshold of ~12 J/cm^2 for the second harmonic. We have focused our attention on determining if the presence of the unconverted fundamental will alter these single wavelength thresholds and in addition whether the growth rates will be affected. In order to define the parameter range of interest we have looked at two specific efficient frequency converters operating in the fluence range of growth of the harmonic wavelengths. The calculations are for a KDP type I, 13 mm thick doubler and a KDP type I, 11 mm thick doubler with a KD*P type II, 9.2 mm thick tripler, and an input spatially flat top fundamental beam. Temporal wave shape is Gaussian and we have considered three pulse widths: 3.5 ns, 10 ns and 20 ns. The calculated unconverted fundamental fluence is plotted versus the output converted fluence for both cases and the results are shown in figure 1. In both cases, the residual red can span the fluence range of 2 to 12 J/cm^2. Since previous measurements[1] at 3ω over a pulse range of 800 ps to 10 ns found weak dependence of the growth on pulse width, the present measurements will cover a residual 1ω range of ~2 to 12 J/cm^2.



(a) (b)

Figure 1. Calculated residual fundamental versus the harmonic wavelength for two convertors.

2. EXPERIMENT

2.1 Laser system and testing parameters

Laser damage initiation thresholds are typically measured with small beam laser systems where the beam profile is Gaussian and of diameter on the order of 1-mm. To make measurements of laser damage growth that are relevant to large beam areas such as are found on high energy laser systems, it is necessary to use a beam with an area large relative to the initial damage size. At LLNL, a unique laser facility can provide a large area, 1053 nm beam along with a high rep rate. The laser is the SLAB laser system[4], a Nd: glass zig-zag slab amplifier, with SBS phase conjugation producing a near diffraction limited 1.053 µm output. This is the 1ω wavelength for these experiments, with 527 nm and 351 nm the 2ω and 3ω wavelengths respectively. As used for these experiments SLAB provides a 20 J, 1053 nm output pulse, with a 12 nsec FWHM near Gaussian shaped temporal waveform, at a rep rate of 0.5-Hz. The rep rate is limited by the data collection rate, as the laser system can be operated at 5 Hz. This is the beam that is formatted and converted into the appropriate wavelengths used in these experiments.

The SLAB 1-micron beam is image relayed onto the experiment table where it is formatted to 1.7 cm by 1.7 cm and enters a frequency converter system. The frequency converter is a type I KD*P doubler followed by a type II KD*P tripler. It is the converted and unconverted fundamental wavelength that is then varied in the growth measurements. Though each wavelength follows a different path to the beam combiners before the test chamber the individual path lengths are kept equal to each other within less than a nanosecond. Three important features of the test beams are produced by using this scheme. The depleted fundamental spatial profile tends to have better uniformity than the unconverted beam, the temporal pulse width is longer than the unconverted beam and the relative polarizations are as they would be after exiting the frequency converter. The appropriate pair of wavelengths is spatially filtered before being transported to the sample chamber. The key components of the layout for these experiments with the SLAB laser are shown in figure 2. The sample is located in an image relay plane of the laser and the beam size for all wavelengths on the part is nominally 5 mm x 5 mm. The beams are spatially and temporally overlapped at the sample. The laser is incident at 15º. The fluence of each wavelength is independently controlled with a polarizer/waveplate combination.

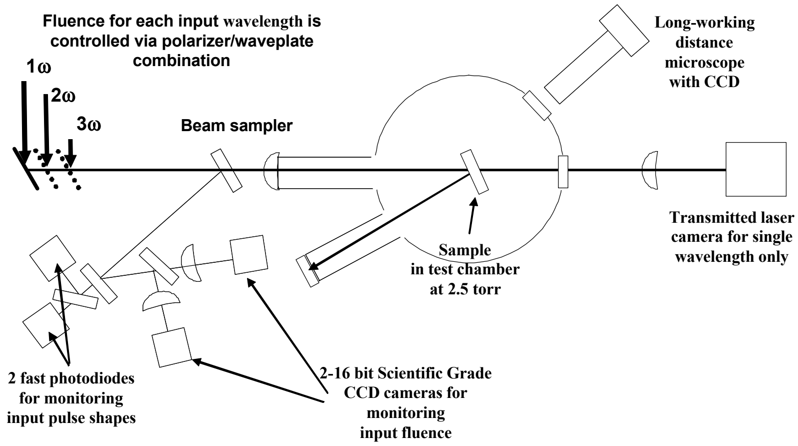
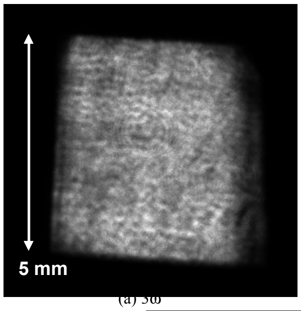
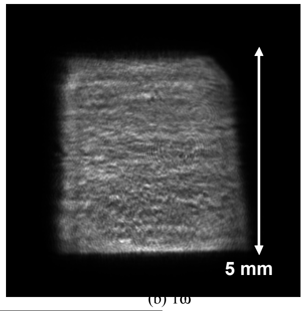


Figure 2. Layout of experiments.

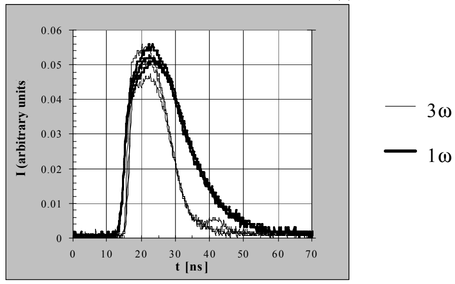
The sample is housed in a stainless steel vacuum chamber, which is located in a class 100 area where samples up to 150 mm x 150 mm in size are handled during loading. For these tests, conducted in air at 2-10 torr, dry filtered high purity air is used to fill the chamber after it has first been pumped out to vacuum.

Laser beam measurements for both test beams on the part include measurement of the temporal pulse shapes, energy and input & output beam spatial intensity distributions for each wavelength. Diagnostics to measure the growth include a white light illuminated, long working distance microscope and CCD camera and a scientific grade CCD camera viewing the transmitted light through the site. The workhorses for the growth measurements are two 16-bit scientific-grade CCD cameras that sample the input beams incident on the part. They are calibrated both for energy and for magnification and are used to set and record the fluence on the sample for each shot. In practice, the camera viewing the beam transmitted through the sample is used to locate the starting damage and the input camera is used to set the local fluence in a 1-mm patch surrounding the site. The lateral growth of the damage site can be measured either from the transmitted camera or from the microscope. Typical images of the converted and residual beams and temporal waveforms on the sample for the combined 3ω and 1ω tests are shown in figure 3a, 3b and 3c respectively. The calculated statistics for the 3ω beam shown in figure 3a is a contrast ratio (rms/average) of 18% over the central 60% of the beam area. The calculated statistics for the 1ω beam shown in figure 3b is a contrast ratio of 21% over the central 70% of the beam area. An overlay of 4 consecutive temporal waveforms is shown in figure 3c, where the average FWHM=11 ns for the 3ω beam and 18 ns for the 1ω beam; also seen in the plot is the relative time of arrival of the two beams with the 1ω beam arriving approximately 2 ns before the 3ω beam. Typical images of the converted and residual beams and temporal waveforms on the sample for the combined 2ω and 1ω tests are shown in figure 4a, 4b and 4c respectively. The calculated statistics for the 2ω beam shown in figure 4a is a contrast ratio of 23% over the central 65% of the beam area. The calculated statistics for the 1ω beam shown in figure 4b is a contrast ratio of 10% over the central 75% of the beam area. An overlay of 4 consecutive temporal waveforms is shown in figure 4c, where the average FWHM=8 ns for the 2ω beam and 17 ns for the 1ω beam with the 1ω beam arriving approximately 3.5 ns before the 2ω beam.



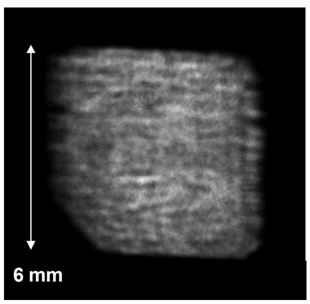


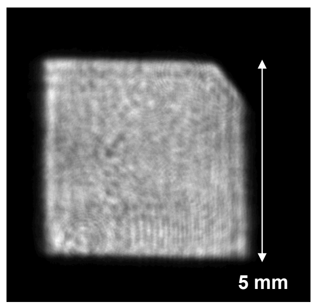
(a) 3ω (b) 1ω



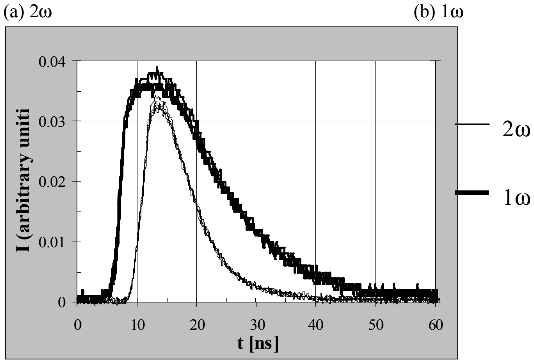
(c) 3ω and 1ω

Figure 3. Typical beam spatial near field and temporal profiles for the combined 3ω and 1ω tests.





(a) 2ω (b) 1ω



(c) 2ω and 1ω

Figure 4. Typical beam spatial near field and temporal profiles for the combined 2ω and 1ω tests.

2.2 Samples

The samples investigated are fused silica, UV grade Corning 7980, 2-inch round 1-cm thick and were super polished by SESO. Laser damage was initiated off-line at 355 nm with a single shot at a fluence level in the 40 to 45 J/cm^2 range with a 7.5 nsec FWHM Gaussian pulse. This high initiating fluence was chosen to produce repeatable damage spots in both size and morphology; even so there were variations in the site morphology. A typical initiated site is shown in figure 5. The sites typically contained multiple pits varying in individual sizes from 10 to 60 µm; some of these pits have a visible crack network associated with them and some pits are joined with adjacent pits.

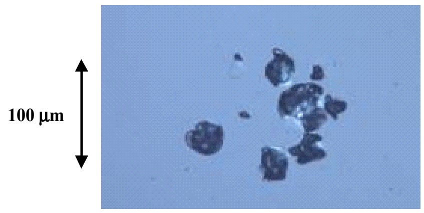


Figure 5. Micrograph of typical initiated site.

3. EXPERIMENTAL RESULTS

3.1 Growth of exit surface damage with both 3ω and 1ω present.

The goal of this work is to obtain the growth rate of laser damage on the exit surface under multiple wavelength irradiation. The result of all growth measurements obtained under conditions where the site was illuminated with both the third harmonic and the fundamental during the entire growth sequence is considered in this section. The site is allowed to grow until the diameter reaches two or more millimeters. At least 50 shots at the working fluences are accumulated before reporting that a site does not grow. In some cases as many as 300 shots were accumulated before reporting a zero growth site.

After each laser shot, the lateral area of the damaged site was measured. The lateral diameter of the damage was calculated from the measured area by assuming a circular equivalent area. A typical growth plot with the effective diameter plotted vs. shot number is shown in figure 6. Also, the average fluences in an area surrounding the growing site are plotted. In this case, the 3ω fluence was held at 5.2 J/cm^2 and the 1ω fluence was held at 7.0 J/cm^2. As was found for single wavelength growth, growth with two wavelengths simultaneously present exhibits a lateral diameter increase which is exponential with shot number. The data is fit to an exponential curve given by

$$D = D_0 e^{\alpha N} \tag{1}$$

where D is the effective lateral diameter of the damage, N is the shot number and α is designated the growth coefficient. The lateral growth spurts seen in the plots are typified by a few shots where crack growth seen on the perimeter is followed by apparent spallation of material with this cycle repeating itself. The exponential fit to the data in figure 6 is shown along with the R-squared value for this fit. All of the sites tested show comparable fits to the data.

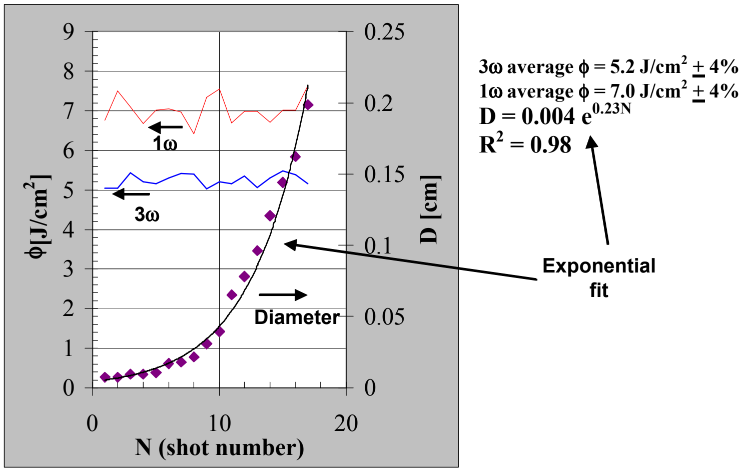


Figure 6. Typical lateral growth behavior showing exponential growth with shot number.

The growth behavior plotted in figure 6 was obtained from the transmitted laser beam during the growth sequence.

Plots of the growth coefficient vs. fluence for many sites shot with various pairs of fluences show a threshold behavior for growth as a function of the total fluence as can be seen in figure 7 where both the growth and no growth data are plotted. A linear fit to all the non-zero data is shown as the dark solid line.

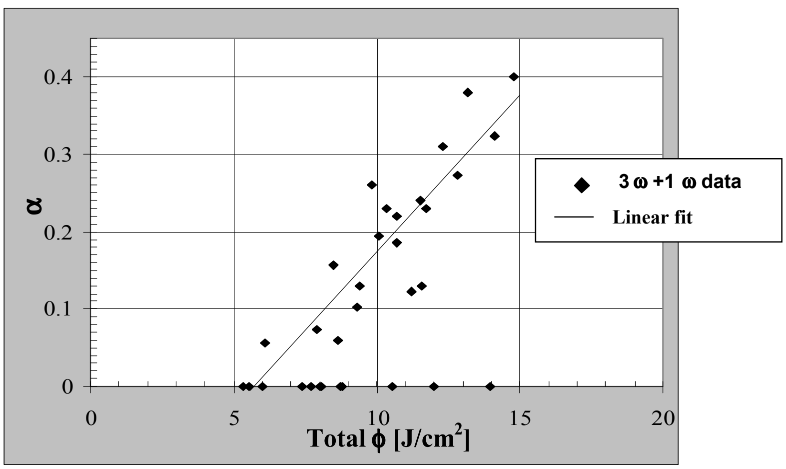


Figure 7. Growth coefficients for combined 1ω and 3ω vs. sum fluence.

The linear fit to the data, $\alpha = 0.041\ F - 0.233$ with an $R^2 = 0.7$, shown in figure 7 predicts a growth threshold of 5.7 J/cm^2; though some sites did not grow at fluences greater than this threshold. In figure 8 we have plotted all the sites that grew along with the growth data measured with only 3ω present.[1] For this plot, the linear fit to the data obtained with 3ω only is given by $\alpha = 0.030\ F - 0.193$ with an $R^2 = 0.8$ which predicts a 16% lower growth threshold: 4.9 J/cm^2. The slope difference between the two linear fits of figures 7 & 8 is less that 5%. With the exception of two sites the no growth sites in figure 7 were obtained when the 3ω component of the sum fluence was less than 4.9 J/cm^2. The data shown in figure 8 suggests that the growth characteristics are determined by the total fluence.

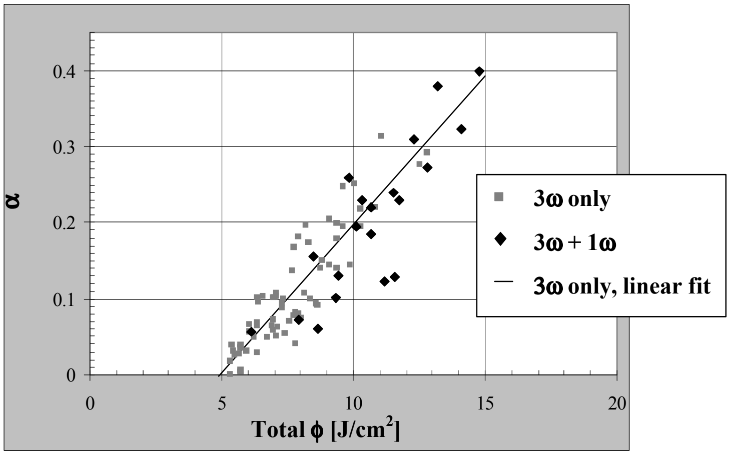


Figure 8. Plot of growth coefficients for 3ω only and 3ω plus 1ω vs. total fluence.

We have replotted the combined wavelength data by parameterizing the 3ω component of the total fluence; this is shown in figure 9. This plot suggests that if the 3ω fluence is below the 3ω growth threshold then the growth coefficient may be less than that which would have been measured if all the fluence had been delivered at 3ω.

Deleted: that

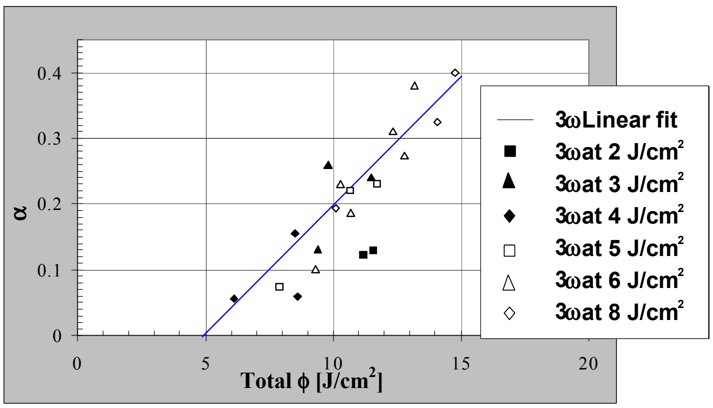


Figure 9. Combined 3ω and 1ω growth with 3ω component specified.

3.2 Growth of exit surface damage sites with combined 2ω and 1ω irradiation.

The growth coefficients previously obtained with 2ω only[2] are plotted versus fluence in figure 10. Only sites having measurable growth are included on the plot. No growth was initiated at fluences below 12 J/cm^2, even on very heavily damaged sites. A linear fit to the measured data valid for fluences $\geq$12 J/cm^2 is given by $\alpha = 0.0094\ F - 0.0423$ with an $R^2 = 0.8$ is shown in figure 10. Based on the observed 2ω threshold, 2ω fluences for the combined wavelength tests are chosen to be less than this threshold.

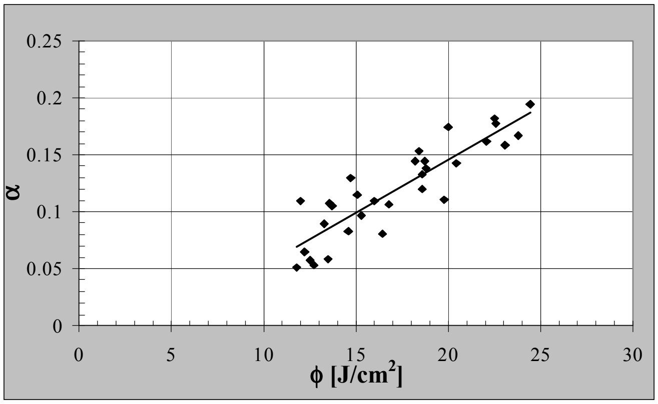


Figure 10. Growth coefficients for 2ω only.

The combined 2ω with 1ω growth test results are shown in figure 11 where growth coefficients for all sites including no growth sites are plotted versus the sum fluence and the data is parameterized with the 2ω fluence. Also included on the plot are both the 3ω and 2ω linear fits shown in figures 8 and 10 respectively.

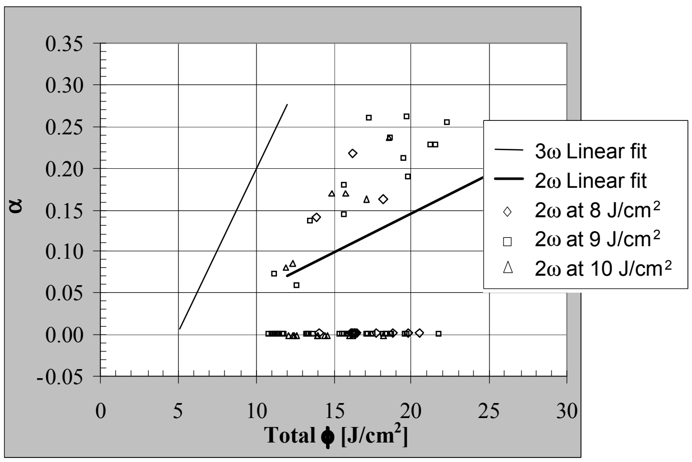


Figure 11. Growth coefficients for combined 2ω and 1ω vs. the total fluence.

In figure 12, the non-zero growth data from figure 11 is shown along with non-zero growth coefficients obtained with 1ω only.[3] As can be seen from this plot the combined fluence coefficients superimpose well with the single wavelength data obtained with 1ω only.

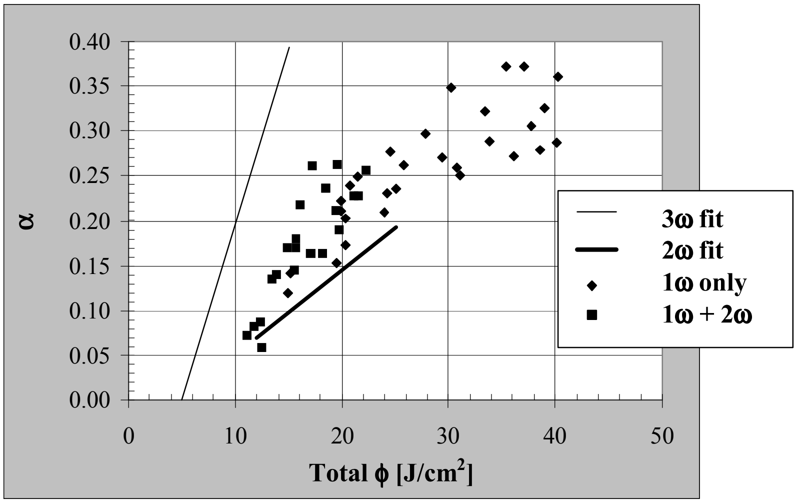


Figure 12. Growth coefficients for 1ω only along with 1ω + 2ω growth data.

3.3 Summary of all wavelength exit surface growth.

All single wavelength data along with the multiple wavelength growth data have been combined into one plot shown in figure 13. Also shown on this plot is a second order fit to the 1ω only growth coefficients, given by $\alpha = -0.00036F^2 + 0.028F - 0.21$ with $R^2 = 0.9$. This data fit, over the 15 to 40 J/cm^2 range where the data was obtained, seems to suggest a saturation effect in the growth coefficients; as of now we have been unable confirm this by measuring growth coefficients at fluences greater than 40 J/cm^2 as surface damage initiation dominates at these high fluences.

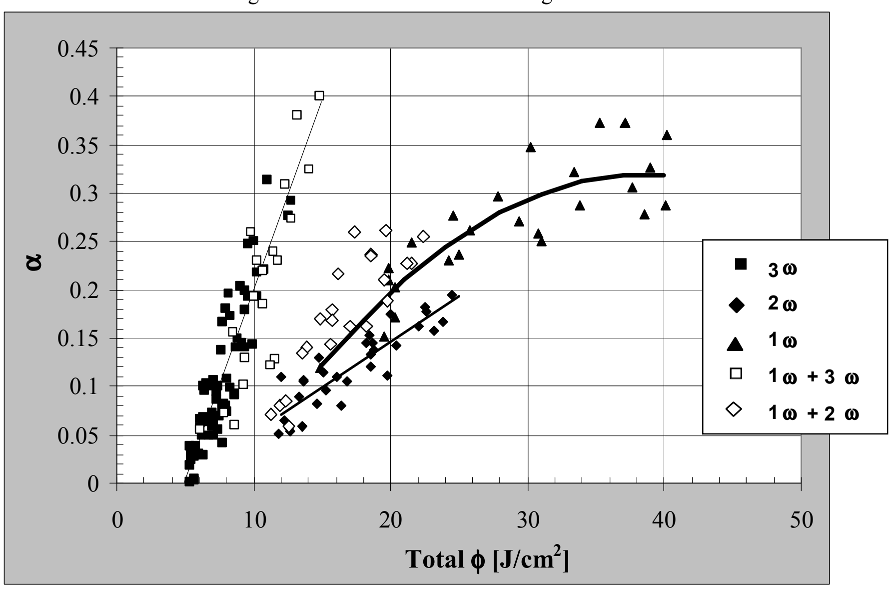


Figure 13. All non-zero growth data.

4. DISCUSSION

Formatted: Keep with next, Keep lines together

We have shown that unconverted 1ω must be considered in the operations of frequency converted laser system when multiple wavelengths are present together on fused silica optical components. For both pairs of wavelengths, if a damage site grows it is the total absorbed energy that determines the damage growth rate. This is reasonable if we assume that absorption at one or both wavelengths leads to plasma generation during the growth event and that all subsequent incident laser energy is absorbed. For both pairs of wavelengths, the threshold for growth is not altered significantly from the single harmonic threshold provided that it is the total fluence that is considered. For the combined 3ω with 1ω case, once growth is enabled, the growth rate is similar to the 3ω only curve and the total energy determines the growth coefficient. This is in contrast to the combined 2ω with 1ω case, where again it is the total energy that determines the growth coefficient but now it corresponds to the 1ω only curve. In both cases, the measured coefficient corresponds to that at the wavelength having the greatest damage growth rate. The reason for this behavior is not yet explained. The fact that the observed single wavelength growth rates are not monotonic in wavelength needs to be understood as part of this eventual explanation

ACKNOWLEDGEMENTS

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

REFERENCES

1. M. A. Norton, L. W. Hrubesh, Z. Wu, E. E. Donohue, M. D. Feit, M. R. Kozlowski, D. Milam, K. P. Neeb, W. A. Molander, A. M. Rubenchik, W. D. Sell, and P. J. Wegner, "Growth of laser-initiated damage in fused silica at 351 nm", *Proc. SPIE* 4347, 468, 2000.
2. M. A. Norton, E. E. Donohue, W. G. Hollingsworth, J. N. McElroy, and R. P. Hackel, "Growth of laser-initiated damage in fused silica at 527 nm", *Proc. SPIE* 5273, 236, 2003.
3. M. A. Norton, E. E. Donohue, W. G. Hollingsworth, M. D. Feit, A. M. Rubenchik, and R. P. Hackel, "Growth of laser-initiated damage in fused silica at 1053 nm", *Proc. SPIE* 5647, 197, 2004.
4. C. B. Dane, L. E. Zapata. W. A. Neuman, M. A. Norton, and L. A. Hackel, "Design and Operation of a 150 W Near Diffraction-limited Laser Amplifier with SBS Wavefront Correction," *IEEE J. Quantum Electronics*, **31**, pp. 148-163, 1995.