Preprint
UCRL-JC-144297

# Localized $CO_2$ Laser Treatment for Mitigation of 3$\omega$ Damage Growth in Fused Silica

*R.M. Brusasco, B.M. Penetrante, J.A. Butler and L.W. Hrubesh*

This article was submitted to Boulder Damage Symposium on Optical Materials, Boulder, CO, October 1-3, 2001

U.S. Department of Energy

Lawrence Livermore National Laboratory

**December 7, 2002**

# Localized $CO_2$ laser treatment for mitigation of 351 nm damage growth on fused silica

Raymond M. Brusasco*, Bernie M. Penetrante, James A. Butler and Lawrence W. Hrubesh

Lawrence Livermore National Laboratory, P.O. Box 808-L-228, Livermore, CA 94551

## ABSTRACT

A technique for inhibiting the growth of laser-induced surface damage on fused silica, initiated and propagated at the 351 nm laser wavelength, has been investigated. The technique exposes the damage sites to single pulses of a $CO_2$ laser operating at the 10.6 µm wavelength at or near beam focus. This method results in a very localized treatment of the laser damage site and modifies the site such that laser damage does not propagate further. A laser damage site initiated with a single pulse of 355 nm laser light at ≈ 45 J cm$^{-2}$ and 7.5 ns pulse duration grows rapidly upon further illumination at 8 J cm$^{-2}$ with 100% probability. Treatment of these sites with single pulses of 10.6 µm laser light for one second at a power level of between 17 and 37 Watts with a beam diameter of 5 mm alters the damage site such that it does not grow with subsequent 351 nm laser illumination at 8 J cm$^{-2}$ 10 ns pulse duration for > 1000 shots. The technique has been found to be 100% effective at stopping the growth of the laser damage.

## 1. INTRODUCTION

Historically, the study of laser damage has been dominated by consideration of the mechanisms for the formation of the damage sites. Such information is useful, but must be taken in context when considering the design, construction and operation of a major laser facility.[1] In the larger context, it is both possible and desirable to separate the phenomenon of laser damage into coupled, but distinct, aspects. The first aspect is the genesis of laser damage, which usually begins as a collection of perturbations (in the bulk of the material or upon its surface) and which is very small in spatial extent. The second aspect is the evolution of laser damage over time with exposure to successive laser pulses after initial creation.[2] There is a tendency for the severity of the material perturbation, which defines laser damage, to increase over time.[3] Most of the study of laser damage concerns itself with the first aspect, namely the origin and nature of the initial damage site. Much work has been done to identify the site, understand the nature of the precursors to the formation of the site and to effect changes to the optical materials to limit the formation of laser damage.

In the context of laser operations, though, it is the second aspect which causes concern. Unless laser damage were totally inhibited, the concern is that any laser damage on an optic may increase in severity with use such that laser performance limitations, such as beam obscuration, intensity modulation and light scatter, will grow to unacceptable proportions. Assuming that one will always have some laser damage to contend with, one can ask whether there are methods available which can inhibit the growth of that laser damage such that laser performance limits are avoided to the maximum extent possible. The subject of this paper is to address this issue by exploring one method found to inhibit the growth of laser damage after it has occurred. This is a somewhat novel concept in considering laser damage study and effort.

The methodology for mitigating the growth of laser damage under consideration in this work is the exposure of the $SiO_2$ surface laser damage site to pulses from a $CO_2$ laser, operating at 10.6 µm wavelength. The use of $CO_2$ lasers to modify and process materials has a long history.[4] Even in the area of laser damage study, $CO_2$ lasers have been used in the past as a possible method to control the formation of laser damage.[5-8] A study was done some years ago to investigate the efficacy of $CO_2$ laser treatment on the 3ω laser damage threshold.[9] The results of those tests were inconclusive. It should be pointed out however, that what has not been considered previously is the possibility of using $CO_2$ laser treatment on laser damage sites to render them benign in terms of growth of the site during subsequent use wavelength operation. Such use is the subject of this investigation.

## 2. EXPERIMENTAL DETAILS

A 1 kW continuous wave Rofin-Sinar RS-1000 carbon dioxide laser system attached to a computer controlled stage capable of manipulating a sample to 10 µm precision in each of three orthogonal directions was used as the source of the damage mitigating laser pulses. Fused silica flat substrates of Corning 7980 material, 50 mm in diameter and 10 mm thick and polished by SESO, were used as the test specimens. Pre-initiated laser damage sites were placed on the substrates by exposing sites to single pulses from a tripled Nd:YAG laser operating at 355 nm, 0.8 mm beam diameter and 7.5 ns pulse duration at approximately 45 J $cm^{-2}$. Figure 1 presents an optical micrograph of a typical damage site produced in this fashion. Figure 2 shows a stylus profilometry trace (Tencor AlphaStep 500 or similar device) of the damage site shown in figure 1. The morphology of the initiation site is a cluster of pits which individually are fairly small in lateral extent and possess steeply sloped sides.

Sites were mitigated by single pulse exposures to the $CO_2$ laser beam for one second. After exposure, the sites were then tested in the Slab Lab test facility. The Slab Lab test facility has been described previously.[1,2] All sites were tested at 351 nm, ≈ 10 ns pulse duration, at a fluence between 8 and 14 J $cm^{-2}$ in air. A typical lifetime test run was 1000 shots. The sites were monitored during the test and examined in detail after the tests were completed.

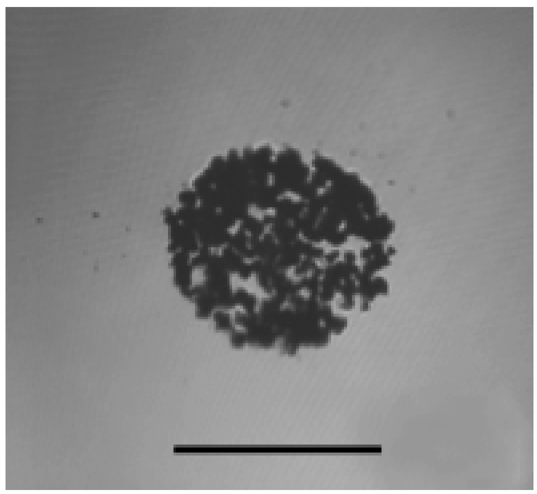

Figure 1. Photograph of a damage site in fused silica initiated by a single 45 J $cm^{-2}$ pulse. The black line in the figure is approximately 600 µm in length.

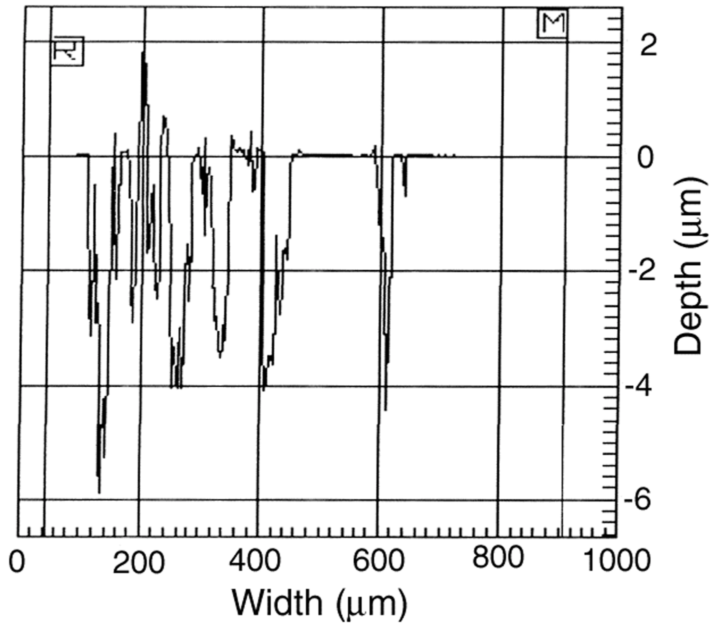


Figure 2. Stylus profilometry trace of the damage site in figure 1.

## 3. RESULTS AND DISCUSSION

Initially, we hypothesized that an effective treatment of a laser damage site must require the "excavation" of that site to remove any offending material and render the surface area smooth and the subsurface crack free. Figure 3 shows an optical micrograph of the site shown in figure 1 after exposure to a single pulse of $CO_2$ laser light for one second. The laser power was 37 watts and the full beam diameter was 5 mm. The beam diameter was established by burn tests using polycarbonate sheets. The resulting pit formed is smooth and featureless. Figure 4 is a stylus profilometer trace of the pit, which shows that the excavation depth is much deeper than the accessible portions of the pits that existed before $CO_2$ laser exposure (compare with figure 2). These results suggest that significant change in the optic material has occurred and also suggests that offending defects have been removed.

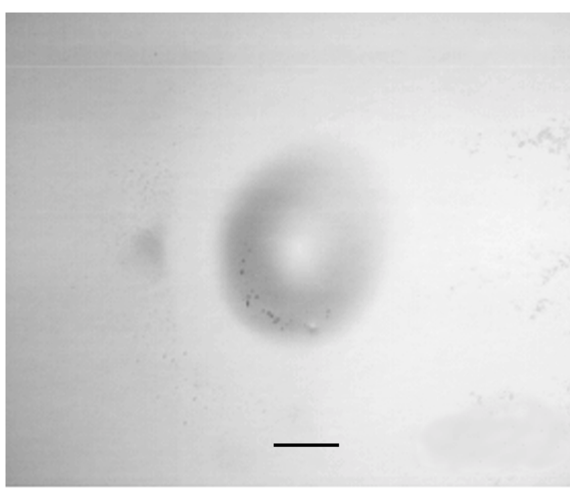

Figure 3. Photo of the damage site in figure 1 after a single pulse of $CO_2$ laser light. The laser power was 37 watts, 5 mm beam diameter and one second duration. The size fiducial is 500 µm in length.

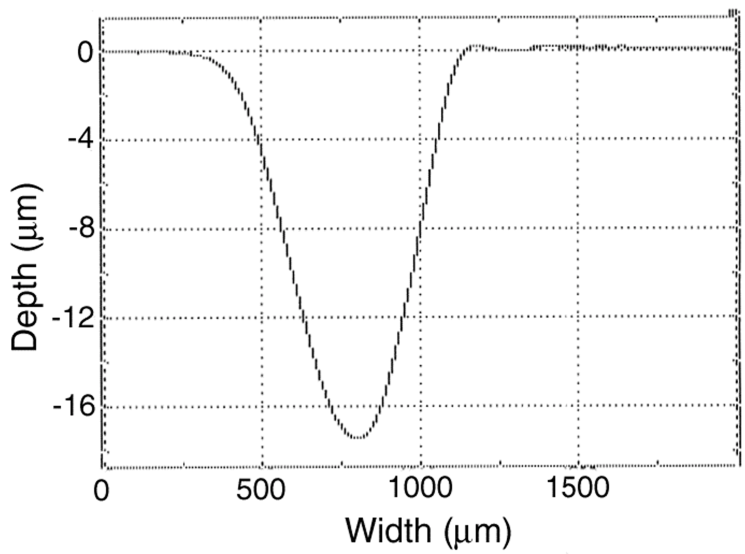


Figure 4. Stylus trace through the pit shown in figure 3.

Table I lists samples mitigated in this manner and the results from laser damage tests performed in Slab Lab to determine the efficacy of the treatment method. In all cases, sites that were treated in this manner survived 1000 shots at 8 J $cm^{-2}$, 10 ns, with no growth in the site and no visual change to the site after irradiation. Some of these sites were retested at fluences up to 14 J $cm^{-2}$ with the same result – no growth in the damage site and no visual change to the area. These tests reliably establish the fact that vigorous $CO_2$ laser treatment of initiated damage sites can inhibit the growth of those sites under further 3ω irradiation.

Table I

3ω damage testing on sites "excavated" by $CO_2$ laser treatment

| Sample | Site | Treatment | Shots to Growth |
|---|---|---|---|
| SC40036 | B | 50 W $CO_2$, 1s | 1000+ |
| | A | 50 W $CO_2$, 1s | 1000+ |
| | D | 50 W $CO_2$, 1s | 1000+ |
| SC40037 | B | 37 W $CO_2$, 1s | 1000+ |
| | A | 37 W $CO_2$, 1s | 1000+ |
| | C | 37 W $CO_2$, 1s | 1000+ |

We performed some experiments to determine whether less aggressive treatments to a laser damage site would be beneficial. Figure 5 shows a micrograph of a laser damage site initiated in the typical manner while figure 6 shows the same site after a mild $CO_2$ laser treatment. In this case, a mild treatment condition consists of the pulse length being maintained at one second with the laser power reduced to ≈ 17 watts while maintaining the beam diameter at 5 mm via polycarbonate burn tests. Visually, the effect of the $CO_2$ laser pulse is to smooth out the high contrast features evident in figure 5. It is clear from examination of figures 5 and 6 that the pattern of pit clusters is maintained, indicating that the laser treatment has had only a mild physical effect on the damage site in that the broad feature patterns remain distinct. Stylus profilometry of the site indicated that evaporation of the surface had been minimal; the depression within the laser damage site was only about 0.5 μm deep. This result is to be contrasted with the more vigorous treatment as shown in figure 4, where material evaporation resulted in a deep pit.

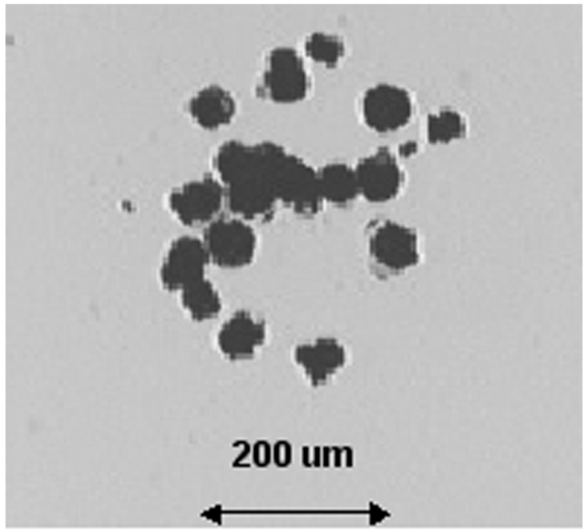


Figure 5. Photo of a damage site before a mild $CO_2$ laser treatment.

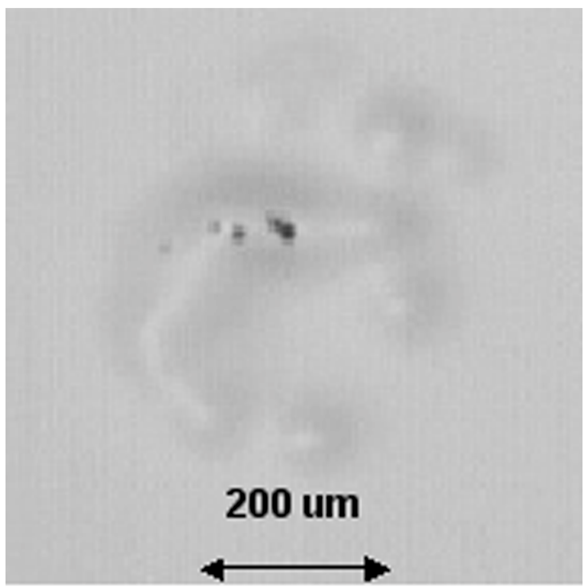


Figure 6. Photo of the damage site in figure 5 after a mild $CO_2$ laser treatment. The $CO_2$ laser power was 17 watts, beam diameter 5 mm and exposure time one second.

The micrograph in figure 6 suggests that there is remnant damage at the bottom of the initial damage pit after $CO_2$ laser treatment. Figure 7 shows a micrograph of these features at 10 times magnification and reveals these remnant spots to be bubbles. Presumably, these bubbles formed during the material reconstruction process that occurs during the $CO_2$ laser treatment. There is no evidence that bubbles were produced during the initial laser damage initiation. In any case, laser damage testing of these sites produced no visible change in the appearance of this site and no growth in damage after 1000 shots at 8 J cm$^{-2}$, 10 ns. Three sites such as this were tested and none were found to grow. Retesting at 14 J cm$^{-2}$ also showed the same effect.

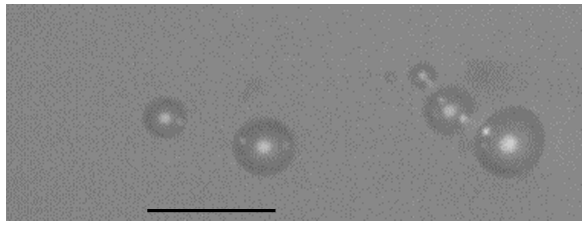

Figure 7. Photo of the dark objects in figure 6 at higher magnification. The remnant objects are found to be bubbles. The line fiducial in the photo is 20 μm.

In conclusion, preliminary tests of spot mitigation of damage growth on fused silica laser damage sites using a $CO_2$ laser beam show great promise. Sites initiated at 3ω and which have a 100% tendency to grow at fluences of 8 to 14 J $cm^{-2}$ (10 ns) are altered by both vigorous and mild exposures to $CO_2$ laser light. The behavior of these sites changes from 100% growth probability to 100% no-growth probability as a result of either type of mitigating exposure. Future work will be directed towards optimizing the conditions for best damage growth mitigation at the lowest possible 10.6 μm laser fluence as well as investigating the effect of type of surface and the treatment level needed to stop growth of damage initiated at lower fluences.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Walter Grundler, Randy Barksdale, Stephen Maricle, Mary Norton, Bill Molander, Kurt Neeb and Eugene Donohue for technical assistance and discussions. This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

## REFERENCES

1. M.R. Kozlowski, R. Mouser, S. Maricle, P. Wegner and T. Weiland, "Laser Damage performance of fused silica optical components measured on the Beamlet Laser at 351 nm," Proceedings of SPIE Vol. 3578, Laser-Induced Damage in Optical Materials: 1998, 436, 1999.
2. L.W. Hrubesh, M.A. Norton, W. A. Molander, P.J. Wegner, M. Staggs, S. Demos, J.A. Britten, L.J. Summers, E.F. Lindsey and M.R. Kozlowski, "Chemical etch effects on laser-induced surface damage growth in fused silica," 32nd Annual Symposium on Optical Materials for High Power Lasers, Boulder, CO, October 16-18, 2000. Laser-Induced Damage in Optical Materials: 2000, SPIE Vol. 4347, 553, 2001.
3. F.Y. Génin, C.J. Stolz and M.R. Kozlowski, "Growth of laser-induced damage during repetitive illumination of $HfO_2$-$SiO_2$ multilayer mirror and polarizer coatings," Proceedings of SPIE Vol. 2966, *Laser-Induced Damage in Optical Materials: 1996*, 273, 1997.
4. For example, see J.T. Robinson, O.B. Cecil, and R.R. Shah, "Method for removal of minute physical damage to silicon wafers by employing laser annealing", U.S. Patent No. 4390393, June 28, 1983.
5. P.A. Temple, D. Milam and W.H. Lowdermilk, "$CO_2$ laser polishing of fused silica surfaces for increased damage resistance at 1.06 μm", *National Bureau of Standards Special Publication 568*, 229, 1979.
6. P.A. Temple and M.J. Soileau, "1.06 μm Laser-Induced Breakdown of $CO_2$-Laser-Polished Fused $SiO_2$," *NBS Spec. Publ. 620*, 180, 1981.
7. P.A. Temple, W.H. Lowdermilk and D. Milam, "Carbon dioxide laser polishing of fused silica surfaces for increased laser-damage resistance at 1064 nm," *Appl. Opt.*, **21**, 3249, 1982.
8. P.A. Temple, S.C. Seitel and D.L. Cate, "Carbon dioxide laser polishing of fused silica: recent progress," *NBS Spec. Publ. 669*, 130, 1984.
9. A.J. Weber, A.F. Stewart, G.J. Exarhos and W.K. Stowell, "An investigation of laser processing of silica surfaces", *National Institute of Standards and Technology Special Publication 752*, 542, 1986.