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ABSTRACT

Replacing growing damage sites with benign, laser damage resistant features in multilayer dielectric films may enable large mirrors to be operated at significantly higher fluences. Laser damage resistant features have been created in high reflecting coatings on glass substrates using femtosecond laser machining. These prototype features have been damage tested to over 40 J/cm^2 (1064nm, 3ns pulselength) and have been shown not to damage upon repeated irradiation at 40J/cm^2. Further work to optimize feature shape and laser machining parameters is ongoing.

Keywords: Laser machining, laser damage mitigation, femtosecond laser ablation, thin films

1. INTRODUCTION

The 3ns damage fluence of 1053/1064nm high reflecting thin film coatings is over 40 J/cm^2 for high quality films and damage fluences of 100 J/cm^2 and greater are not uncommon for 1 cm^2 test areas.[1] However, the operational fluence of large (~0.25 sq. meters) thin film dielectric 1053nm high reflectors is limited to only about 25 J/cm^2 for 3 ns pulses by the damage susceptibility of a few defects[2]. Once damaged these sites grow upon repeated exposure to fluences above ~15 J/cm^2. If a damage site is created, its growth will require replacement of the entire optic; thus a few small micron-sized defects limit the operational fluence and lifetime of a large mirror.

In this paper, a defect is defined as a localized area of the coating with a significantly lower laser damage threshold. The defect may be a disruption in the multilayer dielectric stack due to substrate imperfections, coating material inclusions, coating material variation or impurity, or foreign material inclusions. Laser damage fluences discussed are for 1053/1064nm, 3ns pulses, unless noted otherwise, 1053 nm and 1064 nm damage fluences are equivalent and are not distinguished. Damage is a change to the coating that is greater than 30 microns in diameter or grows upon continued irradiation. Small "nodule ejection" sites are not considered damage as they have a small diameter (less than 15 microns), do not grow, and do not have a significant impact on the mirror or laser system performance.

2. DEFECT REMOVAL

2.1 Defect replacement concept

Laser damage thresholds of 1053nm mirror coatings are defect driven[2]. The damage fluences of these defects are distributed across a wide fluence range. The defects that limit the laser damage threshold of large optics to about 25 J/cm^2 are rare relative to the total number of defects. These rare (low spatial density) sites tend to have a density of about 1 defect per 1000 cm^2 based on internal damage numbers. Although process improvements have greatly reduced and will further continue to reduce coating defects, production of defect free mirrors remains an elusive goal.

Unfortunately, the damage sites that are produced by these rare defects tend to grow at fluences as low as 15 J/cm^2. Replacement of these defects and damage sites with benign features could increase the operational fluence limit of large mirrors. If each damaging feature or damage site is replaced with a benign pit or feature, the new operational fluence is increased to the fluence determined by the damage initiation rate (the number of damage sites created at a given fluence), number of mitigation pits allowed and the damage threshold of the benign pits. If the laser damage fluence of the replacement feature is significantly greater that the damage fluence of the defect or the growth fluence of a damage site, the increase in operational fluence could be significant.

2.2 Benign Pit Defined

The replacement feature(s) must meet the following requirements to be viable as benign pits for defect replacement:

1. Laser Damage Threshold: The replacement feature must survive fluences significantly higher that the defect or site it replaces. The initial goal is that the feature does not damage under repeated irradiation at 35 J/cm^2.
2. Size: The replacement pit must be able to replace damage features up to 1mm in diameter.

2.3 Historical Efforts

Previous efforts have been made to create benign pits with various laser techniques in addition to MRF and single point diamond machining.[2] These efforts have yielded features that have laser damage thresholds of 25 J/cm^2 or lower, which would not increase the operational fluence of the optic. Ongoing efforts in mechanical machining of benign pits may yet produce high fluence replacement features, but success has not yet been demonstrated.

2.4 Laser Survivability Considerations

Crucial to the success of the replacement feature is its ability to survive high laser fluences. Regardless of the technique used, the process of mitigating the defect will modify the surface topology and create new air/material interfaces. Laser ablative processes deposit energy and generate shock waves in the coating, potentially modifying the coating materials. Physical machining techniques may induce stresses, create cracking, and embed cooling or polishing compounds in the coating as contaminates.

In addition to potential damage to the material structure, the replacement feature will interact with the incoming laser energy creating localized electric field intensification inside the coating structure, potentially reducing the laser damage fluence. The pit edge morphology, pit shape, and edge angle affect the electric field intensification and should therefore impact the laser damage fluence[3].

3. FEMTOSECOND LASER MACHINING

3.1 Femtoscond laser machining

Femtosecond laser machining offers advantages over previous techniques that may enable high damage fluence features[4,5,6]. The ultra short pulses create multi-photon excitation and enable “metal-like” laser machining of dielectric materials[7]. In areas where the laser beam intensity is below the multi-photon excitation levels there is little energy deposition as the materials have very little absorption at the chosen laser wavelength. The ultra short pulses carry very small amounts (~0.5-5μJ) of energy and do not deposit significant heat into the remaining material. The small per pulse energy combined with high repetition rates enable sufficient material removal rates while reducing the per pulse impact. Figure 1 provides a graphical comparison between femtosecond and nanosecond laser machining.

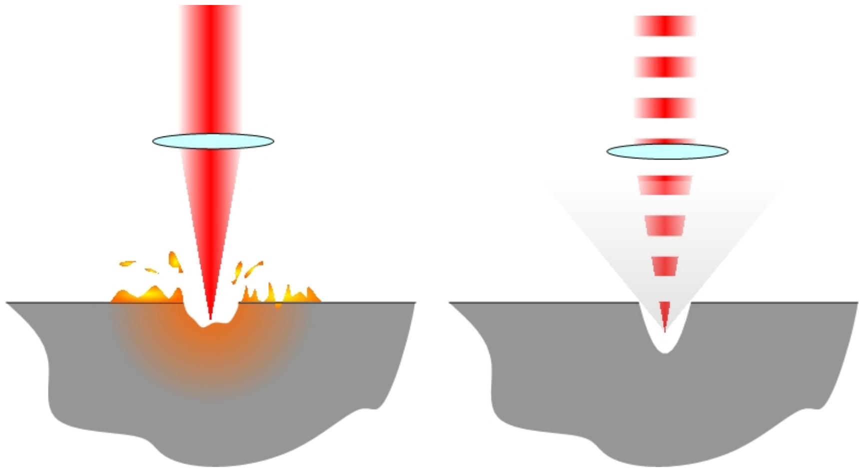


Figure 1. Graphical comparison of nanosecond (left) and femtosecond (right) laser machining. The femtosecond machining yields features with much less or no molten debris and less heat deposition into the material.

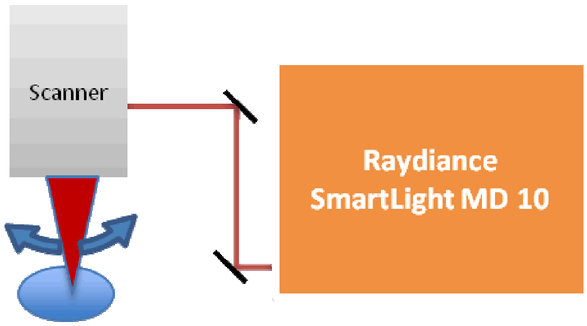
3.2 Raydiance SmartLight Laser

Femtosecond laser machining of laser damage resistant features has been considered and attempted in the past, but has failed due to insufficient laser power to machine features in a reasonable time and the complexity, lack of reliability and cost of traditional femtosecond systems.

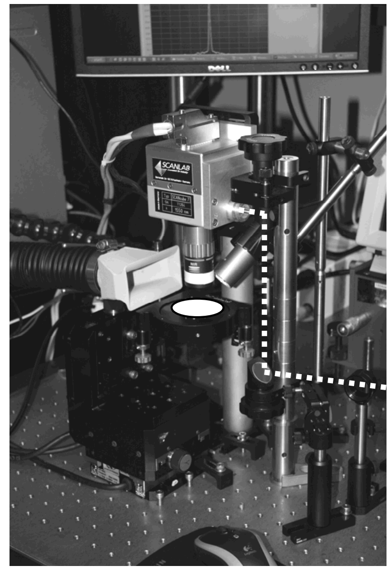
Laser systems recently produced by Raydiance Inc, yield high average power, femtosecond pulses at high repetition rates enabling rapid machining of mitigation features. In addition, the compact size and turn-key nature of the system makes deployment of the laser into a mitigation tool more attractive.

3.3 Machining of prototype features

Numerous prototype mitigation features have been created in 2” diameter witness samples. To date, round and square pits have been created with nominal dimensions 1mm across and 8-50 microns deep. The pit dimensions and geometry were chosen on the basis of available area, machining system capabilities, and testing considerations. All features were machined as vertical cylinders or pits due to limitations of the working distance and the Rayleigh range of the machining system. Future efforts will take the related work by Qiu[3] on electric field intensification into consideration with the creation and testing of tilted or shaped features.



(a)



(b)

Figure 2. Schematic diagram of laser machining system (a) and photo of Raydiance application development system (b). Laser path is shown with dotted white line. Sample location shown by white oval. The laser is outside the frame to the right.

The machining of the features was accomplished at Raydiance Inc, in Petaluma, CA on their application development system shown in figure 2. The application development system is a flexible platform used for capability demonstrations and process development. The system is equipped with stages and mounts to allow processing of various samples and enable a wide range of system parameters. The pits were machined by raster scanning a ~5micron femtosecond pulsed spot across the surface to create the desired pit shape and size. The major components of the system and settings used for machining of the test features are shown in table 1.

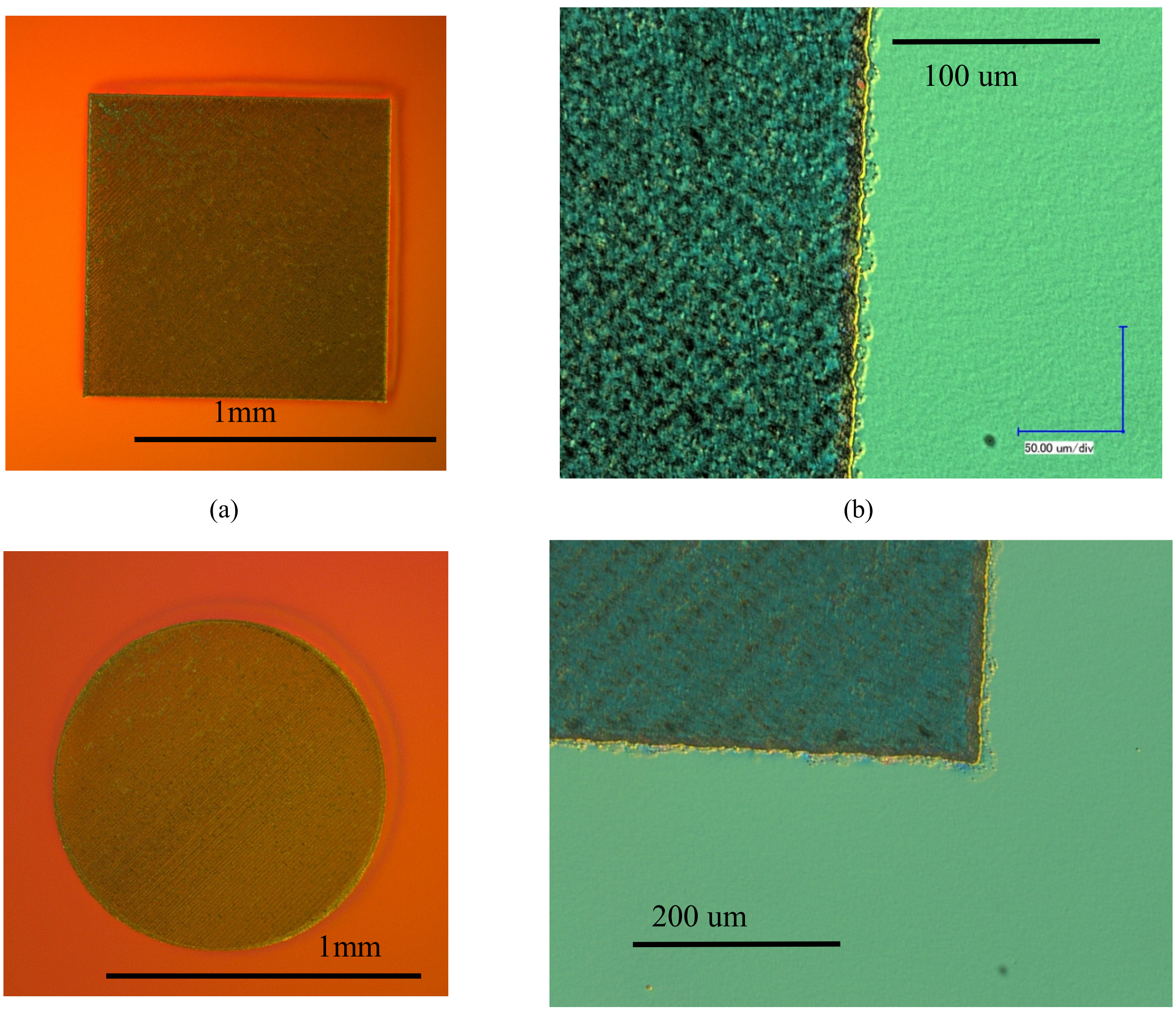
Table 1. Components of machining system and machining parameters.

Laser	Raydiance Discovery 1.3+
Wavelength	1550 nm
Beam delivery	ScanCube 7 with Mitutoyo 1550 lens
Pattern	Crosshatch with ± 45 degree fill & 0.003mm fill
Repetition Rate	100 kHz
Pulse Energy	0.38 uJ on target
Pulse Width	568 fs
Machining time	3 sec
Spot Size	5.5 um (FWHM)
Spot Overlap	~75%

4. RESULTS

4.1 Physical characterization

The pits created femtosecond machining in multilayer dielectric coatings have very good physical qualities. The coating surrounding the pit appeared to be largely unaffected, except for occasional removal of the top layer for a few microns outside the feature. The pit walls were vertical. The base of the pits were roughened with visible lines from the machining raster pattern. The edges of the pit were slightly scalloped, potentially due to the raster scan parameters. It is unknown whether this scalloped edge is an advantage in that it may break up the incident laser energy reducing intensification and raising the damage fluence, or creates additional points of potential failure, lowering the damage fluence. Representative images are shown in figure 3.



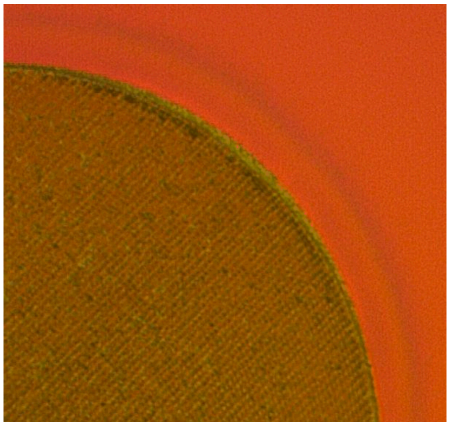
(a) (b)

(c) (d)

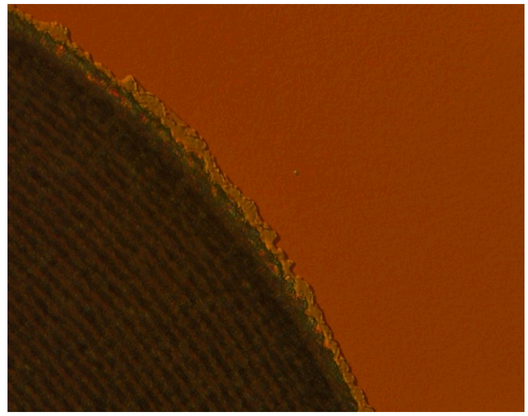
Figure 3: Images of square (a) and circular (c) replacement features machined into mirror coatings. Pits are approximately 10 microns deep. Detail of the square pit edges are show small delimitation of the top layer or layers (b) and corner detail (d).

A debris field was deposited around part of the pit and shaped by an exhaust system. Most of the debris rinsed away quite easily, however, some remained and was well adhered to the coating. More aggressive cleaning techniques were not employed due to potential risk of damaging the mitigation feature and the surrounding coating.

Demonstration of a technique using strippable coatings to eliminate debris from the surface was successful. A thin layer of photoresist is applied to the optic prior to the machining operation. Removal of the photoresist after machining removes the debris field. Figure 4 shows the results of this technique with no detectable debris field present. Damage testing features with and without debris fields showed no significant difference in the laser damage threshold.



(a)



(b)

Figure 4: Images of upper right corner of circular pits showing debris field (a) and clean feature without debris field (b)

4.2 Damage Results

The laser damage threshold of femtosecond laser machined pits has been tested by Spica Technologies by repeatedly raster scanning (beam overlap at 90%) the pit and surrounding coating at 3 J/cm^2 increments similar to the method described by Borden[8]. Laser damage thresholds of greater than 40 J/cm^2 have been repeatedly demonstrated with damage occurring in the range between 35 and 49 J/cm^2. The laser damage fluence of the pits occurs at about 5-10 J/cm^2 below the damage fluence of the surrounding film. The samples used in tests to date have been older coatings with small area damage fluences lower than current optics. It is unknown if higher small area damage fluences will yield higher pit damage fluences, or if the fluence is limited to about 40 J/cm^2 by the pit alone. Figure 5 shows the cumulative number of damage sites for three representative features as a function of the laser fluence. For these three sites, no damage occurred until 46 J/cm^2 was reached.

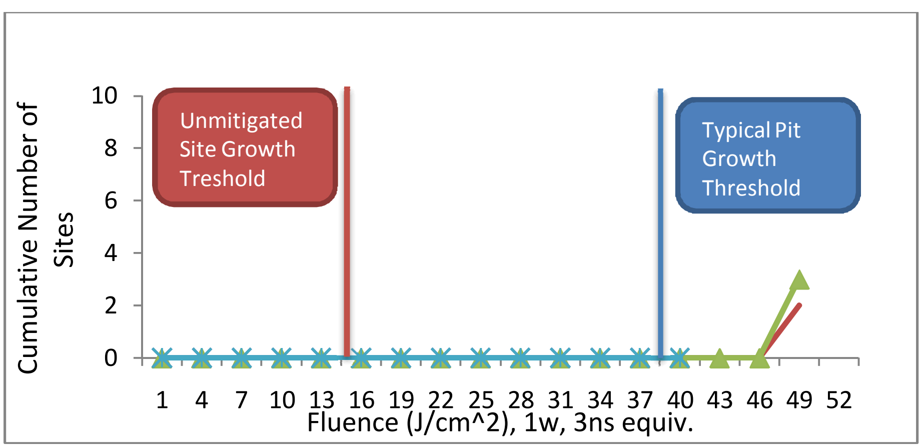


Figure 5: Plot showing damage testing of three benign pits showing no damage through 43 J/cm^2 for these three features.

Table 3. Summary of laser damage fluence values for replacement pits

	Value	Note
Maximum Pit Laser Damage Fluence	49 J/cm^2	S-pol, 45 degrees
Minimum Pit Laser Damage Fluence	35 J/cm^2	P-pol, 45 degrees, (sample was 14 years old, other sites on same sample survived 40 J/cm^2)
Typical Pit Damage fluence	40 J/cm^2	

Damage to the replacement pits always occurred on the leading edge of the features as shown in figures 6 and 7. This may be due to e-field intensification, reflections at the pit edge, pit edge morphology or other causes. Tilting the pit such that the sidewall angle matches the laser angle of incidence may eliminate this edge effect and yield higher laser resistance.

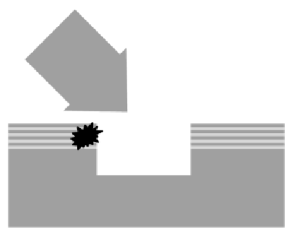
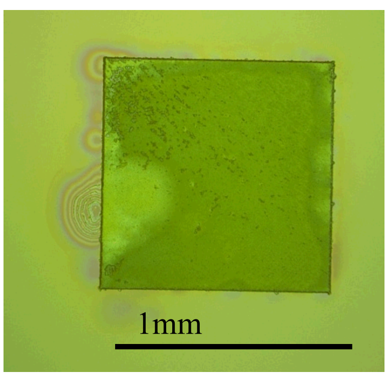
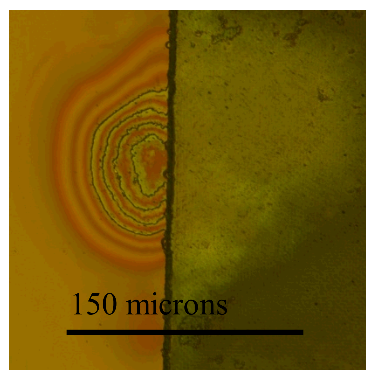


Figure 6: Diagram showing typical damage location. For laser beam incident from upper left, damage occurs initially on left side of pit.



(a)



(b)

Figure 7: Images of laser damage showing overview with intial damage shown on left side of image (a). The damage on the right side occurred at higher fluences. A high magnification image (b) shows layer by layer removal of the coating, centered just outside the coating; a possible indication of electric field enhancement.

5. CONCLUSIONS

Benign pits have been created with femtosecond laser machining. The machined features exhibit excellent physical characteristics and have survived laser fluences in excess of 35 J/cm^2 which is at least 20 J/cm^2 higher than the typical damage growth threshold on large mirrors. Techniques to eliminate the debris field have been successfully demonstrated however, no impact on the laser resistance of the machined pit has been observed.

Current results have been obtained with no process or pit geometry optimization. Process parameters and pit details were determined by the machining system capabilities and nominal settings. Future work to optimize the shape of the machined pit and process parameters to further enhance the laser damage fluence is ongoing. It is thought that by controlling the side wall angle and improving the edge morphology, the laser damage fluence may be increased above 40 J/cm^2.

6. ACKNOWLEDGEMENT

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REFERENCES

[1] C.J. Stolz, M.D. Thomas, and A.J. Griffin, "BDS thin film damage competition," *Laser-Induced Damage in Optical Materials: 2008*, G. J. Exarhos, D. Ristau, M. J. Soileau, and C. J. Stolz eds., Proc. SPIE 7132 (2009) pp. 71320C-7.

[2] C.J. Stolz, J. Adams, M.D. Shirk, M.A. Norton, and T.L. Weiland, "Engineering meter-scale laser resistant coatings for the near IR," *Advances in Optical Thin Films II*, C. Amra, N. Kaiser, and H. A. Macleod, eds., Proc. SPIE 5963, 2005, pp. 59630Y-9.

[3] S.R. Qiu, J.E. Wolfe, A. Monterrosa, M.D. Feit, T.V. Pistor, C.J. Stolz, "Modeling of light intensification by conical pits within multilayer coatings", *Laser-Induced Damage in Optical Materials: 2009*, G. J. Exarhos, V. Gruzdev, D. Ristau, M. J. Soileau, and C. J. Stolz, eds., Proc. SPIE 7504, 2010 (this proceedings).

[4] M.D. Shirk and P.A. Molian, "A review of ultrashort pulsed laser ablation of materials," Journal of Laser Applications, **10**, 1998, pp. 18-28.

[5] M. Ali, T. Wagner, M. Shakoor, and P.A. Molian, "Review of laser nanomachining," Journal of Laser Applications, **20**, 2008, pp. 169-184.

[6] X. Liu, D. Du, and G. Mourou, "Laser ablation and micromachining with ultrashort laser pulses," IEEE Journal of Quantum Electronics, **33**, 1997, pp. 1706-1716.

[7] H. Varel, D. Ashkenasi, A. Rosenfeld, M. Wähmer, and E. Campbell, "Micromachining of quartz with ultrashort laser pulses," Applied Physics A: Materials Science & Processing, **65**, Oct. 1997, pp. 367-373.

[8] M.R. Borden, J.A. Folta, C.J. Stolz, J.R. Taylor, J.E. Wolfe, A.J. Griffin, and M.D. Thomas, "Improved method for laser damage testing coated optics," Laser-Induced Damage in Optical Materials: 2005, G. J. Exarhos, A. H. Guenther, K. L. Lewis, D. Ristau, M. J. Soileau, and C. J. Stolz, eds., Proc. SPIE 5991, 2006, pp. 59912A-10.

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