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Mitigation scratch on fused silica optics using CO_2 laser

Liu Chun-Ming[1, *], Yan Zhong-Hua[1], Yang Liang[1], Jiang Yong[2], Zu Xiao-Tao[1],
Wang Hai-Jun[3], Liao Wei[3], Yuan Xiao-Dong[3], Zheng Wan-Guo[3]

[1] School of Physical Electronics, University of Electronic Science and Technology of China,
Chengdu, 610054, China

[2] Joint Laboratory for Extremeconditions Matter Properties,
Southwest University of Science and Technology, Mianyang, 62101, China

[3] Research Center of Laser Fusion, China Academy of Engineering Physics,
Mianyang, 621900, China

[*] Corresponding author: cmliu@uestc.edu.cn or cmliu028@163.com

The scratch on a fused silica surface was treated as a chain of connected damage sites and mitigated one after another using CO_2 laser irradiation. The optical microscopy image shows that a scratch with the width of about 30 μm and length of several millimeters can be completely mitigated without the formation of debris and bubbles. The mitigated scratch can survive under raster scan laser irradiation with the fluency increased up to 11.0 J/cm^2 at 3 ns and 351 nm. On the contrary, the substrate without CO_2 laser mitigation is seriously damaged under this irradiation. The light modulation induced by mitigation is much smaller when the scratch is mitigated before being damaged. The light modulation is about 2 when the distance to the mitigated sample is larger than 20 cm. The birefringence induced by residual stress in the mitigated scratch is measured. The retardance of the mitigated scratch before being damaged is not visible. Therefore, residual stress in this mitigated scratch before being damaged should be not a critical potential risk in laser damage.

Keywords: mitigation, scratch, fused silica, CO_2 laser.

1. Introduction

For a high power laser like the Laser MegaJoule (LMJ) and the National Ignition Facility (NIF), fused silica is widely used as gratings, lens, and vacuum window optics [1–3]. Although surface defects density is greatly decreased with the significant improvement in polishing process, zero defect optics is not yet available [4–6]. The occurrence of laser induced surface damage (LISD) is mainly caused by the presence of residual defects in the optics [7]. The LISD densities are about 0.01 sites/cm^2 with laser fluency ranged from 10–14 J/cm^2 [7]. Since the final optics of LMJ is designed to operate at the fluency as high as 14 J/cm^2, LISD is unavoidable under high laser fluency irradiation. The most important problem considered is that the damage size will grow rapidly with subsequent laser irradiation [8–10], resulting in decreasing of optics stability and lifetime [3, 11].

Scratches are usually the defects which are prone to laser damage due to light intensification, light absorption, and mechanical strength weakening [12, 13]. Taking off scratches by an additional step of polishing is not acceptable because the polishing time is too long. In addition, an additional step of polishing may also spoil the quality of a surface waveform and create new scratches [14]. In order to have the high power laser run well in longer term and higher stability, various techniques of mitigation damage growth have been developed [15]. The CO_2 laser mitigation has been proved to be one of the most effective damage growth mitigation techniques for a surface damage site on fused silica optics [15]. Up to now, CO_2 laser has been used to successfully mitigate surface damage sites on fused silica optics and a lot of new techniques including evaporation and no-evaporation have been reported [16–22]. Furthermore, CO_2 laser irradiation is proved to be a rapid, localized to the scratch and clean in scratch mitigation [14, 23–25]. The concentration of a defect caused by LISD can be significantly suppressed by CO_2 laser exposure [26]. However, the light modulation caused by scratch mitigation using CO_2 laser is only studied by simulation [24].

In this paper, CO_2 laser was used to successfully mitigate surface scratches on fused silica. The mitigated scratches have better laser damage resistance than that of not-mitigated scratches and substrate. The laser induced damage threshold (LIDT) of the mitigated scratches is at least 3.6 times of that of not-mitigated one. The light modulation of mitigated scratches was measured and found to be about 2 at a distance of about 20 cm to the substrate surface. The birefringence induced by residual stress of the mitigated scratch is measured and discussed.

2. Experiments

After the fused silica samples (Corning 7980 polished by Sichuan Oropt Optical Science and Technology Co., Ltd.) being etched in buffered hydrofluoric acid (BHF) (1 wt.% HF + 15 wt.% NH_4F) for 6 to 20 minutes, the scratches on surface were measured by Nikon-LV-100 optical microscopy. To mitigate a scratch, the scratch was treated as a chain of connected damage sites. The chains of connected damage sites were then mitigated one after another using a radio frequency power exited coherence GEM-100L CO_2 laser irradiation with a wavelength of 10.6 μm. The diameter of CO_2 laser beam spot used for mitigation was adjusted to be about 2 mm by passing through a 25 cm focal length ZnSe lens. The ZnSe lens was mounted on a two-dimensional translation stage which can be moved along the laser propagation axis to adjust the lens-to-sample separation. The power of CO_2 laser was measured by a Coherent FieldMax-TO powermeter. The mitigation scheme is shown in Fig. 1. The CO_2 laser irradiation region on the sample is indicated by the area inside the circle, and the scratch to be mitigated is indicated by the black bar which will be moved across the center of CO_2 laser

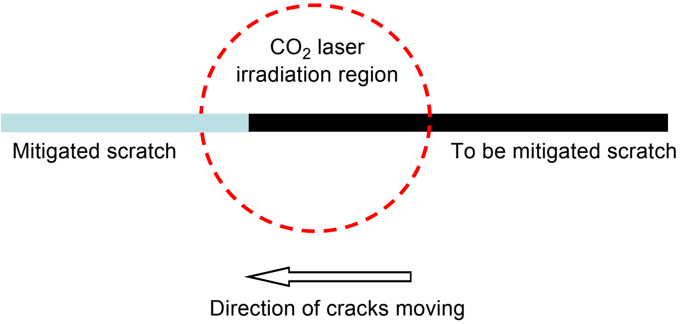

Fig. 1. The mitigation scheme for a scratch.

irradiation region. The length of the scratch to be mitigated in one step is about 80% of the diameter of CO_2 laser irradiation region. After one part of scratch being mitigated, the neighbored part will be moved into the irradiation region and mitigated. The CO_2 laser irradiation region on the sample is clearly visible as a bright red-to-white spot, which is detected by a CCD camera connected to a computer. The CO_2 laser irradiation region detected by the CCD camera is shown on the computer monitor as a white spot and marked on the monitor. The scratches to be mitigated are also detected by the CCD camera and shown on the computer monitor. Since the appropriate temperature for cracks healing is in the region from 1650 to 1810 K [24], the CO_2 laser power and irradiation time were selected to be about 12.3 W and 4 s to have a peak surface temperature of about 1750 K. The peak surface temperature can be calculated using a steady-state approximation with the following equation [16]:

$$\frac{P_0}{a} = \frac{2k\sqrt{\pi}}{1-R}(T_p - T_0)$$

where P_0 is the laser power, a is the $1/e$ laser beam radius, k is the thermal conductivity, R is the reflectivity, T_p is the peak surface temperature, T_0 is the ambient room temperature.

Raster scan was used to measure the laser damage resistance. The laser-induced damage sites were produced on the exit surface of the fused silica sample. In the laser damage resistance measurement, the sample was mounted on a two-dimensional translation stage which can be moved along horizontal (x) and vertical (y) direction. The sample was a raster scan irradiated by a Coherence LPX Pro 2101 XeF laser with a wavelength of 351 nm and a variable spot size. The temporal and spatial shapes of the laser beam are shown in Figs. 2**a** and 2**b**, respectively. The beam spot of XeF laser was adjusted by passing through a 70 cm focal length lens which was mounted on a one-dimensional translation stage which can be moved along the propagation direction. The beam size was measured by a charge coupled device (CCD) camera and then was analyzed using Spiricon Beam Analyzer software. The frequency of XeF laser is selected to be 10 Hz. The pulse duration is about 21.4 ns. When the spot size $x \times y$ is

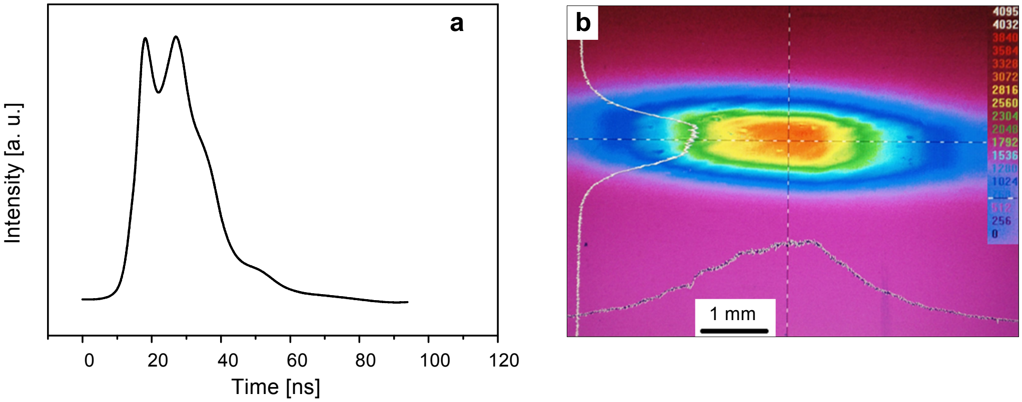

Fig. 2. The temporal (**a**) and the spatial (**b**) distribution of the UV beam.

(2.1 × 0.77) mm^2, the scan speed along x direction is 20 mm/s, and the scan step along y direction is 0.7 mm. When the spot size is (1.2 × 0.43) mm^2, the scan speed along x direction is 10 mm/s, and the scan step along y direction is 0.4 mm. The laser fluency is scaled to 3 ns using the $\tau^{0.6}$ relationship [7]. The laser fluency is increased from 3.0 to 11.0 J/cm^2. The new initiated damage site in one scan loop should be mitigated before a new raster scan. The light modulation of the mitigated scratch was measured by a setup similar as descried in [27]. The setup uses a collimated light beam perpendicular incident on the surface of optics. The mitigated sites are on the rear surface of optics. A CCD camera is used to capture diffraction patterns from the mitigated site. The CCD camera has a field of view of about (7.1 × 5.3) mm^2 and is capable of imaging from 1 to 40 cm downstream from the mitigated site. The residual stress was measured by a PTC-720 cross-polarizer to identify the birefringence.

3. Results and discussion

Figures 3**a** and 3**b** show photographs of scratches before and after mitigation, respectively. The scratches have a width of about 30 μm, and length of about 0.5–3 mm. Figure 3**b** shows that the surface with scratches is locally repaired by CO_2 laser irradiation. The mitigated region has a width of about 160 μm, which is larger than the width of a scratch indicated in Figure 3**a**. This is due to the deformed surface and large laser affected zone [24]. There are no debris or bubbles formation in the mitigation process. Scratches related cracks can be healed during CO_2 laser exposure [24]. The mitigated scratch should be less catastrophic than the not-mitigated ones since any new defects such as debris or bubbles are not introduced.

Figure 4 shows a partly mitigated scratch after a raster scan with 351 nm laser irradiation. The length of the mitigated and not-mitigated scratch is about 2.8 mm. Figure 4**a** is the not-mitigated part irradiated with a fluency of 3.0 J/cm^2. There is one

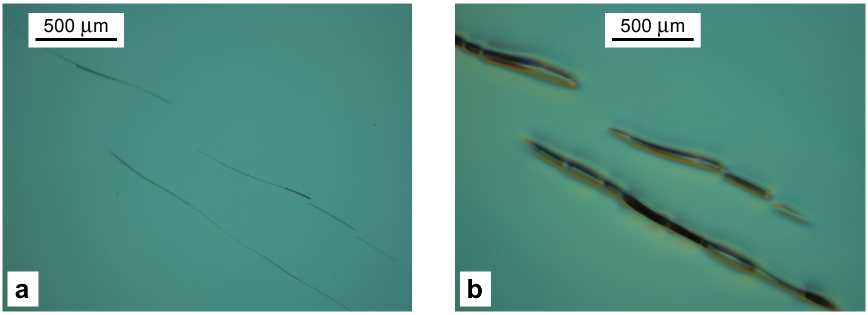

Fig. 3. Photograph of scratches before (**a**) and after mitigation (**b**).

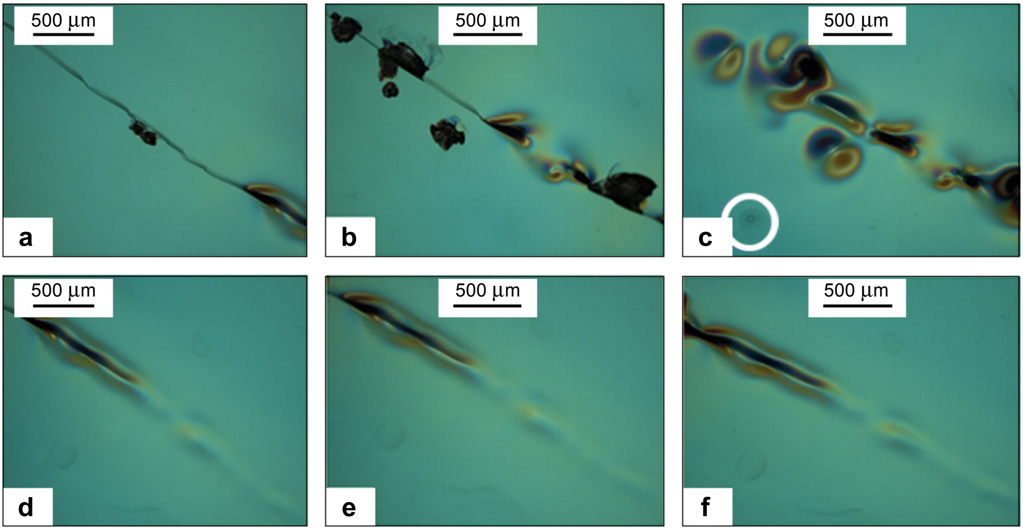

Fig. 4. A partly mitigated scratch after raster scan: the not-mitigated scratch scanned with a fluency of 3.0 J/cm^2 (there is an initiated damage site on the not-mitigated scratch) – **a**; scanned with a fluency of 9.8 J/cm^2 after the initiated damage site in **a** being mitigated (there are four new initiated damage sites) – **b**; scanned with a fluency of 11.0 J/cm^2 after the initiated damage sites and the scratch in **b** being mitigated (there is no new initiated damage sites) – **c**. The mitigated scratch raster scanned with fluency of 3.0 J/cm^2 (**d**), 9.8 J/cm^2 (**e**) and 11.0 J/cm^2 (**f**).

initiated damage site with a size of about 250 μm. After the initiated damage of a site being mitigated, this part of the scratch is a raster scanned again with a fluency of 3.7 J/cm^2, and there is no new initiated damage. This part of the scratch is then a raster scanned with a fluency of 9.8 J/cm^2. There appear three new damage sites on the not-mitigated scratch, and a damage site appears on the substrate (Fig. 4**b**). After the new damage sites appear and the remained scratch is mitigated, a new raster scan with a fluency of 11.0 J/cm^2 is performed and no damage is initiated in the mitigated region

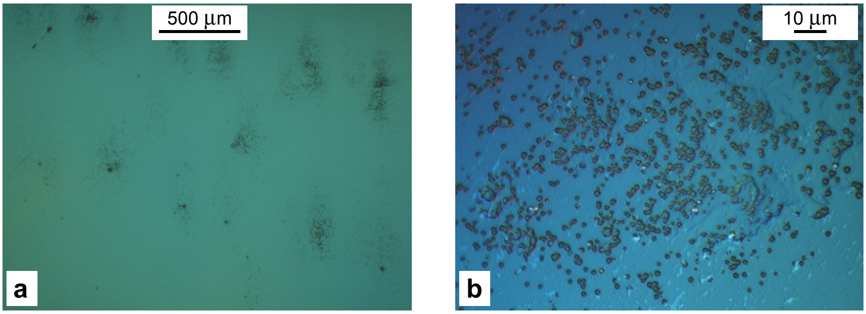

Fig. 5. The substrate after being raster scanned using laser irradiation with a fluency increased up to 11.0 J/cm^2 (**a**), and a damage site magnified (**b**).

(Fig. 4**c**). However, on the lower-left corner of Fig. 4**c** (the region inside the white circle), a ring feature appears. The ring feature may be a damage in the substrate (substrate damage detail is shown in Fig. 5). Figures 4**d**, 4**e** and 4**f** show the mitigated scratch scanned with a fluency of 3.0, 9.8 and 11.0 J/cm^2, respectively. There is no initiated damage site on the mitigated scratch. Thus the LIDT of the mitigated scratch is at least 3.6 times of that of the not-mitigated scratch. Furthermore, the mitigated

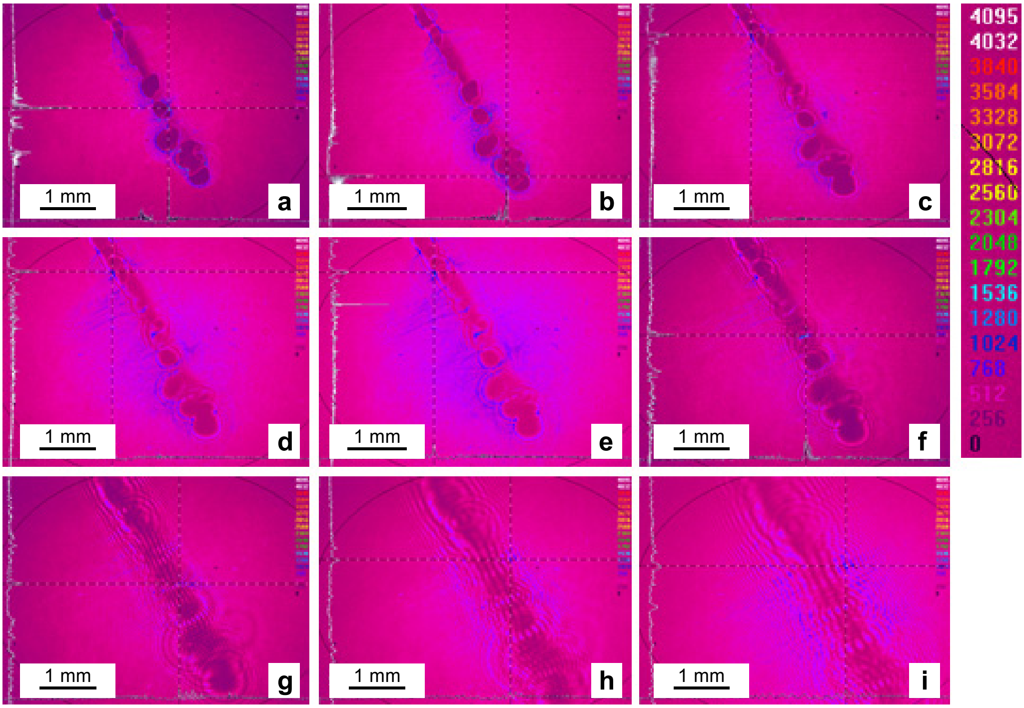

Fig. 6. The light modulation of the mitigated scratch at various distances to the substrate surface: 1 cm (**a**), 1.5 cm (**b**), 3.5 cm (**c**), 4.5 cm (**d**), 5 cm (**e**), 10 cm (**f**), 20 cm (**g**), 30 cm (**h**), and 40 cm (**i**).

scratch has better laser damage resistance than the substrate. Figure 5 shows the substrate after being raster scanned with a fluency increased up to 11.0 J/cm^2. As shown in Fig. 5**a**, the substrate is seriously damaged. The damaged site has a size of about several micrometers and dispersed in a large region (Fig. 5**b**).

Figures 6**a**–6**b** show the light modulation of the mitigated scratch (the scratch was firstly damaged, and then was mitigated) at various distances to the substrate surface (1, 1.5, 3.5, 4.5, 5, 10, 20, 30 and 40 cm, respectively). The image of the mitigated scratch is shown in Figure 4**c**. Compared to the light modulation of single mitigated sites [28], there appear some new characters for the mitigated scratch. There is often an off-axis ring and on-axis intensification of single mitigated sites [22]. The off-axis ring modulation of light induced by a mitigated site is caused by the light scattering from a crater wall of the mitigated site [22]. The on-axis intensification is callused by the raised rim around the mitigated site [22]. However, the intensification of light is not an off-axis intensified ring or an on-axis intensified point for the mitigated scratch. The mitigated scratch has main light intensified regions along the scratch length direction. The distance dependence of light modulation of the mitigated scratch is indicated in Fig. 7. With the distance to a sample surface increasing to 20 cm, the modulation is firstly decreased rapidly, and then oscillates. The modulation approaches to a stable value of about 2 when the distance to the sample surface is larger than 20 cm. The maximum modulation is about 8.

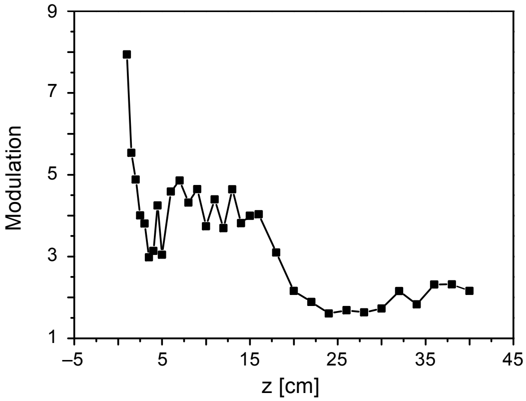

Fig. 7. The light modulation as a function of distance to sample surface for the mitigated scratch with four initiated damage sites.

Figure 8 shows the image of several scratches and one damage site (Fig. 8**a**), the image of mitigated scratches and mitigated damage site (Fig. 8**b**), the light modulation induced by mitigation at a distance of 1.5 cm (Fig. 8**c**), and the light modulation induced by one mitigated scratch as a function of distance (Fig. 8**d**). The white rectangles and white circle in Fig. 8**c** indicate the light modulation induced by mitigated scratches and mitigated damage site, respectively. As seen in Fig. 8**c**, the light modulation induced

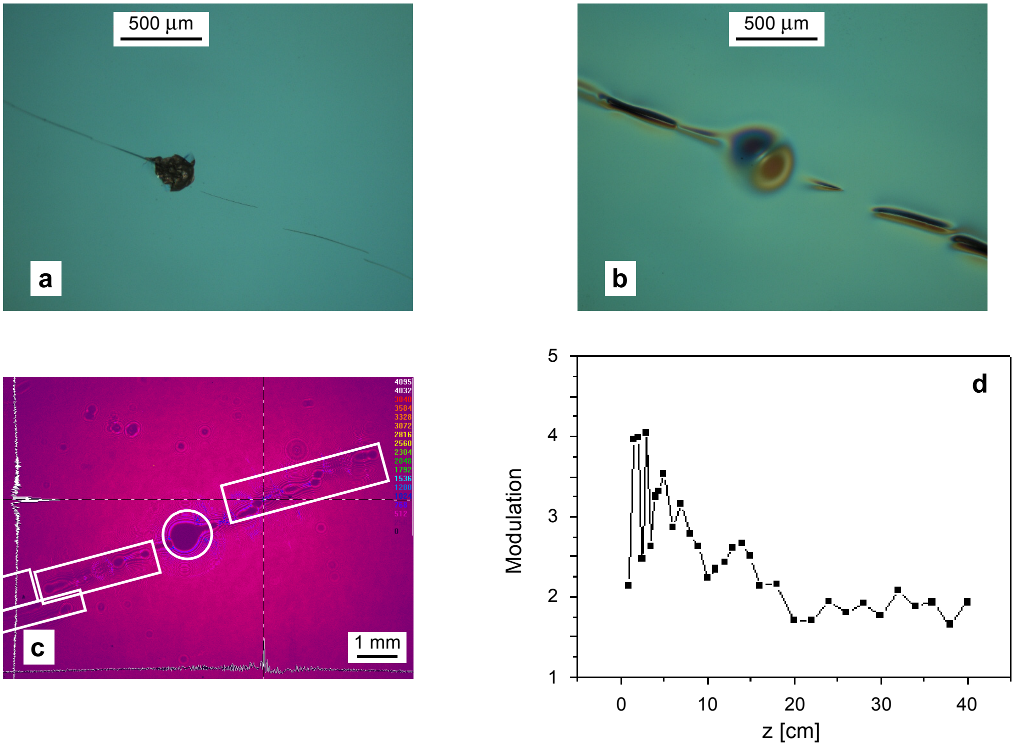

Fig. 8. Photograph of several scratches and a damage site (**a**), photograph of corresponding mitigated scratches and damage site (**b**), typical light modulation of the mitigated scratch (indicated by the cross) at a distance of 1.5 cm to sample surface (**c**), and the modulation induced by mitigated scratch as a function of distance to sample surface (**d**).

by the mitigated scratch is along the direction of the scratch superimposed by some intensified points. These intensified points may be caused by a raised surface [22]. After comparing Fig. 8**d** with Fig. 7 it can be seen that the light modulation exhibits the same character: its oscillates and weakens with distance increasing. The maximum modulation in Fig. 8**d** is about half of that in Fig. 7. This indicates that the scratch should be mitigated before being damaged in order to have a small light modulation.

The birefringence induced by residual stress is shown in Fig. 9. Figure 9**a** is the light pattern for the whole sample (the size of the sample is about (40 × 60) mm^2). The light pattern inside the white circle is from a mitigated damage site, which is similar to that reported in [29]. Figure 9**b** is a light pattern inside the white rectangle in Fig. 9**a**, which is corresponding to the mitigated scratch shown in Figs. 4**c** and 4**f**. The maximum retardance induced by residual stress is located at the mitigated scratch after being damaged (scratch was firstly damaged and then mitigated, corresponding to Fig. 4**c**). The maximum retardance is about 20 nm. The retardance of the mitigated scratch be-

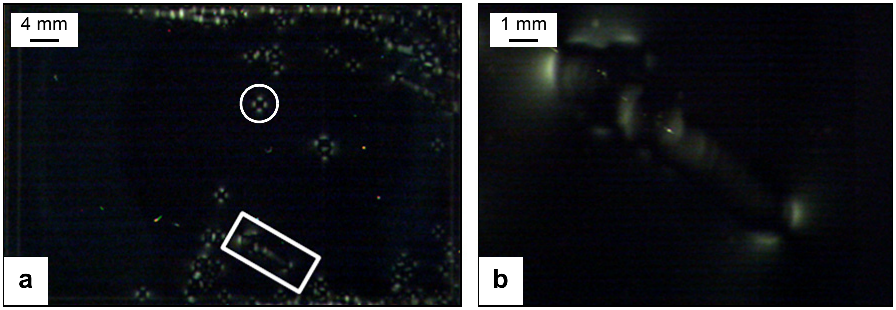

Fig. 9. The birefringence induced by residual stress. Light pattern for the whole sample (the size of this sample is about (40 × 60) mm^2); the pattern inside the white rectangle is the light pattern of the mitigated scratch after being damaged (the photograph of this mitigated scratch is shown in Fig. 4**c**), the pattern inside the white circle is the light pattern of a mitigated site (**a**). The amplified view of the region inside the white rectangle shown in **a** (**b**).

fore being damaged (corresponding to Fig. 4**f**) is not visible. Since LIDT is located in the maximum retardance [29], residual stress induced by the mitigated scratch before being damaged should not be a critical potential risk for laser damage.

4. Conclusion

A strategy of mitigation of a surface scratch on fused silica by CO_2 laser irradiation is presented in this paper. The mitigated scratch has better laser damage resistance than the not-mitigated scratch and substrate. The light modulation caused by the mitigated scratch with and without a damage site is measured experimentally. The scratch should be mitigated before being damaged in order to have a smaller light modulation. The birefringence induced by residual stress of the mitigated scratch is measured. The retardance of the mitigated scratch before being damaged is not visible, indicating that residual stress in the mitigated scratch before being damaged should not be a critical potential risk for laser damage.

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