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Optical modulation of repaired damage site on fused silica produced by CO_2 laser rapid ablation mitigation*

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CO_2 laser rapid ablation mitigation (RAM) of fused silica has been used in high-power laser systems owing to its advantages of high efficiency, and ease of implementing batch and automated repairing. In order to study the effect of repaired morphology of RAM on laser modulation and to improve laser damage threshold of optics, an finite element method (FEM) mathematical model of 351 nm laser irradiating fused silica optics is developed based on Maxwell electromagnetic field equations, to explore the 3D near-field light intensity distribution inside optics with repaired site on its surface. The influences of the cone angle and the size of the repaired site on incident laser modulation are studied as well. The results have shown that for the repaired site with a cone angle of 73.3°, the light intensity distribution has obvious three-dimensional characteristics. The relative light intensity on z-section has a circularly distribution, and the radius of the annular intensification zone increases with the decrease of z. While the distribution of maximum relative light intensity on y-section is parabolical with the increase of y. As the cone angle of the repaired site decreases, the effect of the repaired surface on light modulation becomes stronger, leading to a weak resistance to laser damage. Moreover, the large size repaired site would also reduce the laser damage threshold. Therefore, a repaired site with a larger cone angle and smaller size is preferred in practical CO_2 laser repairing of surface damage. This work will provide theoretical guidance for the design of repaired surface topography, as well as the improvement of RAM process.

Keywords: fused silica, laser repaired surface, optical modulation, finite element method (FEM)

PACS: 42.60.Jf, 42.70.Ce, 46.15.–x **DOI:** 10.1088/1674-1056/ab8206

1. Introduction

Fused silica optics are widely used in terminal optical components of the laser-driven inertial confinement fusion (ICF) owing to their excellent thermal, optical and mechanical performance. However, damage defects inevitably appear on the surface of fused silica during the process of high-power laser shooting. Moreover, the size of the surface damage increases rapidly under the subsequent high-power laser irradiation,[1,2] which seriously affects the stability and service life of optical components. Surface damage of fused silica optics has become the main factor of limiting the output energy of high-power laser device.[3]

It has been widely accepted that CO_2 laser repairing can greatly inhibit the growth of surface damage with small repaired area and excellent light transmission. This CO_2 laser repairing method can effectively improve the laser damage resistance of fused silica optics as well.[4–9] To deal with the problems occurred in the traditional non-evaporative repair technology (e.g., small repairable damage pit, difficulty to control the repairing process and large raised rim around the repaired site),[10–13] researchers in Lawrence Livermore National Laboratory proposed a novel repairing method of CO_2 laser rapid ablation mitigation (RAM).[14] This method uses an ultrafast laser beam to scan and remove the damage material on the surface of fused silica optics, forming a smooth conical crater to achieve the purpose of laser damage mitigation. RAM has the advantages of excellent repair quality, high efficiency, and easy to implement batch and automated repairing,[15–17] which has been already applied in USA National Ignition Facility,[3] France Laser Mega-Joule,[18] China huge laser facility.[19] However, in the process of practical localized CO_2 laser repairing of surface damage, it is found that the repaired surface morphology has a certain modulation effect to the incident laser. In particular, poor quality repaired surface will cause strong light field distortion and local light intensification, leading to the component itself to be damaged again under the irradiation of subsequent laser. Even it is harmful to operation of downstream optics.[20,21] Therefore, it is a hot topic for researchers to study the effect of repaired morphology of RAM on laser modulation and to improve the

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laser damage threshold of fused silica.

Bass *et al.*[14] studied the external optical modulation of fused silica with the conical repaired site through 2D numerical simulation. It was found that the mitigated crater on rear surface could cause the downstream light intensification, and the optics should be installed away from the focus position. Zhang *et al.*[22,23] analyzed the incident laser modulations of the specific repaired morphology and bubbles through finite-difference time-domain (FDTD) calculation. Gaussian mitigated morphology was proposed and adopted in CO_2 laser mitigation. Fang *et al.*[24] used the FDTD method to study the internal electric field distribution of fused silica with the array cracks and the rectangular repaired morphology. In addition, the experimental results showed that the laser damage threshold of mitigated surface was twice that of defective surface. Li *et al.*[25] used scalar diffraction theory to study the effects of Gaussian and conical topography on laser modulation at different downstream distances. It was pointed out that the size of the mitigated crater and the position where downstream optics is installed were very critical. Yang *et al.*[26] employed the 3D-FDTD method to simulate the electric field intensity distribution in the vicinity of particulate contaminants on fused silica surface. Xie *et al.*[27] established a thermal damage analysis model of fused silica materials with surface crack to calculate the distributions of modulated light and temperature field on the optical surface based on the FDTD method. The above-mentioned studies mainly focused on the effects of surface defects or repaired topography produced by non-evaporative mitigation on laser modulation, and most of them are of two-dimensional simulations. There are few systematic studies on the effects of repaired surface produced by RAM on optical properties and laser damage resistance of fused silica. In particular, there is almost no 3D numerical analysis of the near-field intensity distribution for different repaired topographies.

In this work, a mathematical model of 351 nm laser irradiating fused silica optics is developed based on the Maxwell electromagnetic field equations. Aiming at the problems of laser damage resistance of fused silica affected by repaired morphology, the finite element method (FEM) is used to study the 3D near-field light intensity distribution inside optics with repaired site on its surface. The influences of the cone angle and the size of the repaired site on incident laser modulation are also studied. This work can provide theoretical guidance for design of repaired surface topography, as well as improvement of RAM process.

2. Mathematical model

The process of laser propagating inside the fused silica optics is equivalent to the propagation of planar electromagnetic waves inside the component. Based on this theory, the influence of repaired surface morphology on the distribution of light intensity inside the fused silica is studied. Based on the differential form of the Maxwell equation, the electromagnetic field FEM firstly transforms the specific problem to be solved into the boundary value problem of partial differential equations. Then the variational problem is transformed into the extremum problem of the ordinary multivariate function using the split interpolation. Then the numerical solutions of the electric field and magnetic field of each interpolation node are obtained.

In order to evaluate the influence of the repaired surface morphology on light intensity distribution inside the fused silica optics, the relative light intensity (RI) is defined as

$$\mathrm{RI} = \frac{I}{I_0}, \tag{1}$$

where I_0 is the light intensity when the surface of the fused silica optics is the ideal surface, I is the light intensity of the defect surface.

From the perspective of laser damage of optical components, the larger the relative light intensity is, the greater the peak light intensity of the local region gets. When the relative light intensity reaches a certain critical value, it is easy to cause a series of ionization effects (e.g., ionization, two-photon ionization, and collision ionization), which make the fused silica easier to reach its damage threshold. Especially, when the position of maximum light intensity is close to the impurities or the defects distributed in the bulk, fused silica optics are more prone to laser induced damage. Therefore, the distributions of relative light intensity inside fused silica are mainly studied in this work.

The schematic diagram of the conical repaired site on the surface of fused silica optics obtained by CO_2 laser RAM is shown in Fig. 1. Different repair strategies should be used for the damage pits with different sizes, resulting in different repaired sites. The topographical parameters (e.g., depth h, diameter D, and angle α) shown in Fig. 1(c) vary with the repair process.

As the damage pits are mainly concentrated on the rear surface of the fused silica optics, in this work, the 3D numerical analysis of incident laser modulation is carried out for the case that the repaired sites are located on the rear surface. The schematic diagram of the FEM model is shown in Fig. 1(c). The scattering boundary condition (SBC) is added to the boundary that is perpendicular to the direction of incident wave propagation, as the absorption boundary of light wave. The longitudinal approximated infinite propagation of light wave is obtained. While the perfect magnetic conductor (PMC) is added to the interface that is parallel to the direction of the incident wave propagation. The horizontal approximated infinite propagation of light wave is also obtained. The amplitude of electric field E is normalized to 1 V/m,

and the wavelength of incident laser is 351 nm (3ω fundamental frequency). In order to save computing resources and reduce calculation time, the size of the geometric model is $4\times4\times2.2$ μm. The maximum side length of geometric mesh is 50 nm. The optical and electromagnetic parameters of fused silica are shown in Table 1.

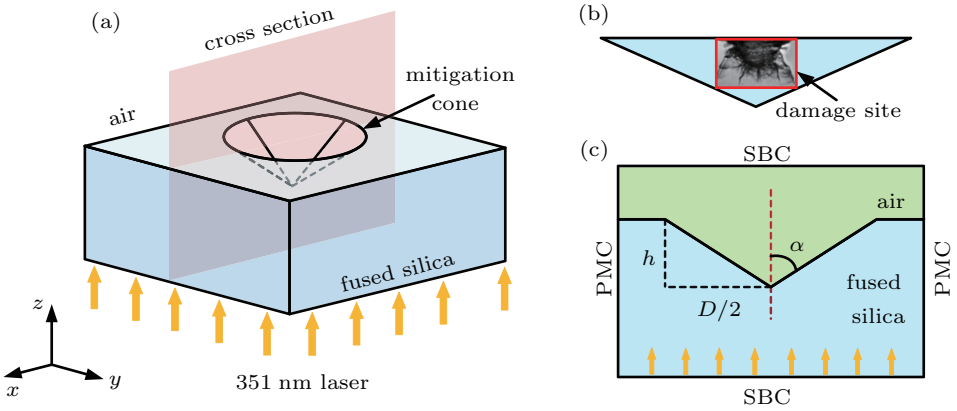


Fig. 1. The schematic diagram of the conical repaired site obtained by CO_2 laser RAM.

Table 1. The optical and electromagnetic parameters of fused silica, i.e., refractive index n, relative permittivity ε_r, relative permeability μ_r, conductivity σ.

Parameter	n	ε_r	μ_r	σ
Value	1.475	2.25	1	0

According to the Fresnel formula, the transmission coefficient of the plane electromagnetic wave in fused silica (in the case of the TE wave) can be defined as

$$r=\frac{E_t}{E_0}=\frac{2n_1}{n_1+n_2}=0.8. \tag{2}$$

When the surface of the fused silica is the ideal surface, the light intensity inside the component can be calculated by

$$\begin{aligned} I_0 &= \frac{1}{2}\mathrm{Re}[\boldsymbol{E}\times\boldsymbol{H}^*]=\frac{1}{2}\sqrt{\frac{\varepsilon}{\mu}}|E|^2 \\ &= 1.2741\times10^{-3}\ \mathrm{W/m^2}, \end{aligned} \tag{3}$$

where ε is dielectric constant, that is, $\varepsilon=\varepsilon_0\varepsilon_r$, $\varepsilon_0=8.8542\times10^{-12}\ \mathrm{F\cdot m^{-1}}$, ε_r is the relative permittivity; μ is magnetic permeability, $\mu=\mu_0\mu_r$, $\mu_0=4\pi\times10^{-7}\ \mathrm{F\cdot m^{-1}}$, μ_r is the relative permeability.

The distribution of light intensity inside the component is uniform, that is, the light intensity at any position is $1.2741\times10^{-3}\ \mathrm{W/m^2}$.

In order to verify the established mathematical model, the 2D FEM models are developed to analyze the distributions of electromagnetic field based on the geometric sizes of array cracks and the rectangular repaired contour on fused silica surface shown in Figs. 1–11 in the literature.[24] The calculation conditions are identical to the literature, and the boundary conditions can refer to Fig. 1. The simulation results are shown in Fig. 2. It is seen that the electric field distributions calculated by the FEM model are consistent with the results obtained by the FDTD method in the literature. The maximum electric field of the array cracks is 1.876 V/m, and the maximum electric field of the rectangular repaired contour is 1.545 V/m. The simulation results of the FDTD are 1.76 V/m and 1.54 V/m, respectively. The results of two calculations are very similar, further verifying the correctness of the established FEM mathematical model in this work.

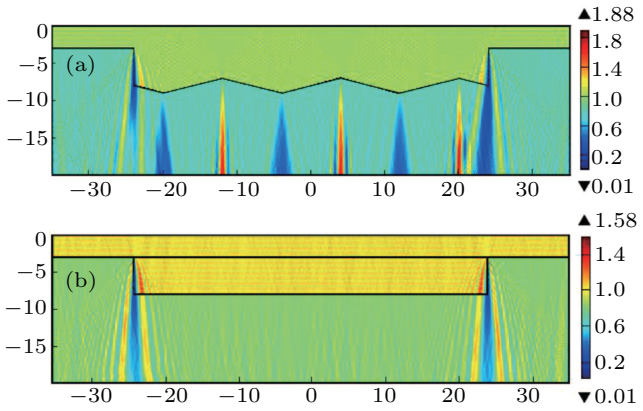


Fig. 2. Electric field distributions around the sites of array cracks and rectangular repaired contour calculated by the FEM method: (a) the electric field distribution around the site of array cracks, (b) the electric field distribution around the site of rectangular repaired contour.

3. Results and discussion

3.1. Analysis of laser propagation in fused silica with repaired site

The laser propagations through fused silica optics with one conical repaired site and two conical repaired sites are studied by geometrical optics theory. The variation curves of light transmittance on repaired contour with respect to cone angle are shown in Fig. 3. It can be seen that the incident light is reflected and transmitted on the repaired contour when laser enters the air from the inside of the fused silica. When

the cone angle is larger ($\alpha > 47.5°$), part of the light is transmitted into the air, and another part is reflected back to the inside of the element at the interface. Whether it is one repaired site or two repaired sites, the light transmittance on the repaired contour remains basically unchanged. When the cone angle is reduced to a certain value ($\alpha = 47.5°$), the light is totally reflected on the repaired contour, and the light transmittance decreases rapidly at this time. The surface with two repaired sites has a greater impact on the laser propagation, the light transmittance is reduced to a lower level. In other words, on the same component surface, the number of repaired sites should be minimized, that is, the repaired area should be reduced to ensure that the laser propagation is not affected. On the other hand, it can be seen from embedded graphs that the reflected and the incident lights are superimposed inside the element, causing the local light intensification inside the bulk, and some focus points are prone to induce new damage. Thus, in the process of practical localized CO_2 laser mitigation, the conical repaired angle should be greater than the critical total reflection angle of 47.5°.

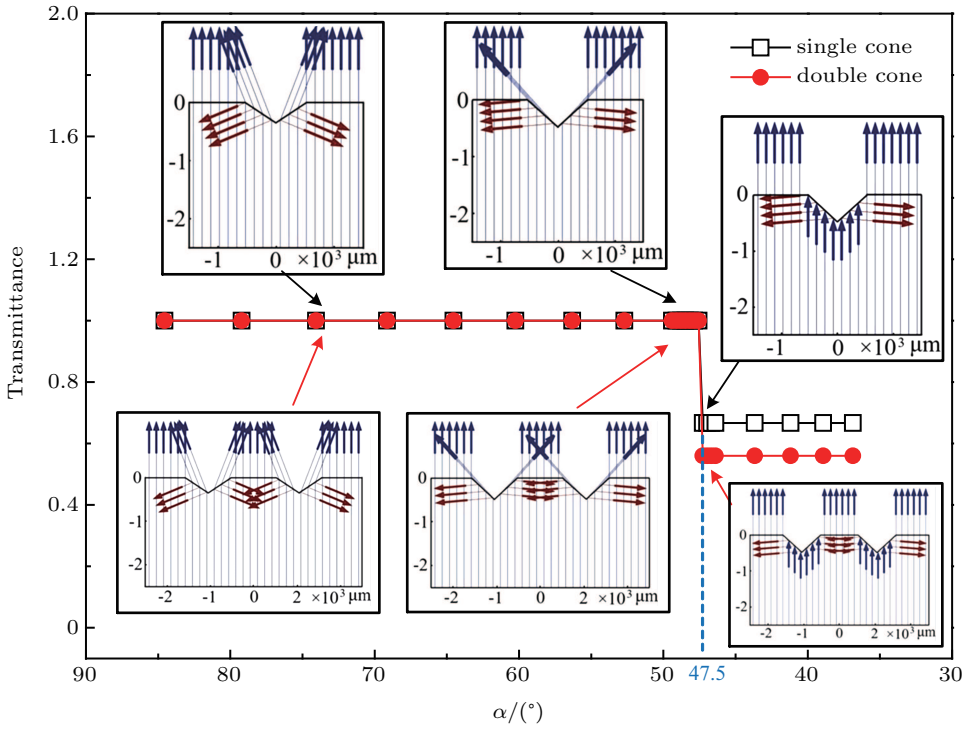


Fig. 3. Light transmittance on repaired contours with one repaired site and two repaired sites.

3.2. Light intensity analysis of repaired site with cone angle of 73.3°

When the conical repaired site has a depth of 0.3 μm and a radius of 1 μm, with the cone angle α of 73.3°, this angle is often used in actual mitigation process, the spatial distribution of relative light intensity inside and outside the element is shown in Fig. 4. As can be seen from Fig. 4, when there is a repaired site with cone angle of 73.3° on the surface of fused silica, the internal electric field of the element is distorted. The maximum relative light intensity is 4.77, which is higher than that of the ideal surface. Additionally, the relative light intensity inside and outside the element shows obvious three-dimensional characteristics. In order to further analyze the influence of the repaired site on the relative light intensity distribution of the element, the relative light intensity distributions of different z-sections and different y-sections are shown in Figs. 5 and 6, respectively.

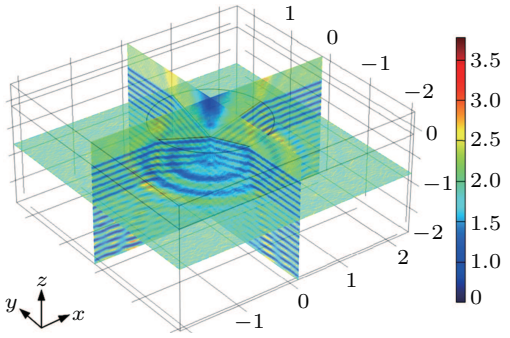


Fig. 4. Spatial distribution of relative light intensity inside and outside the fused silica optics.

It can be seen from Fig. 5 that the maximum relative light intensities of each z-section do not increase continuously with the increase of the section depth, but fluctuate up and down after reaching the maximum. Inside the element, due to the superposition of incident light and reflected light, the relative light intensities on each z-section are distributed circularly, and the central value is lower. The maximal relative light intensity

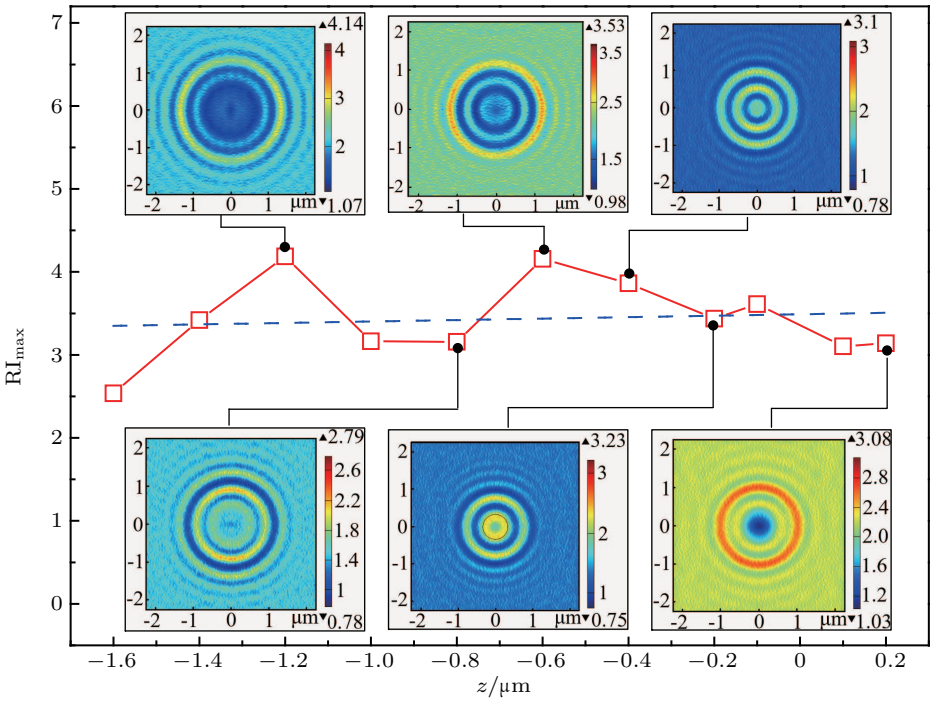


Fig. 5. Relative light intensity distributions at different z-sections with a cone angle of 73.3°.

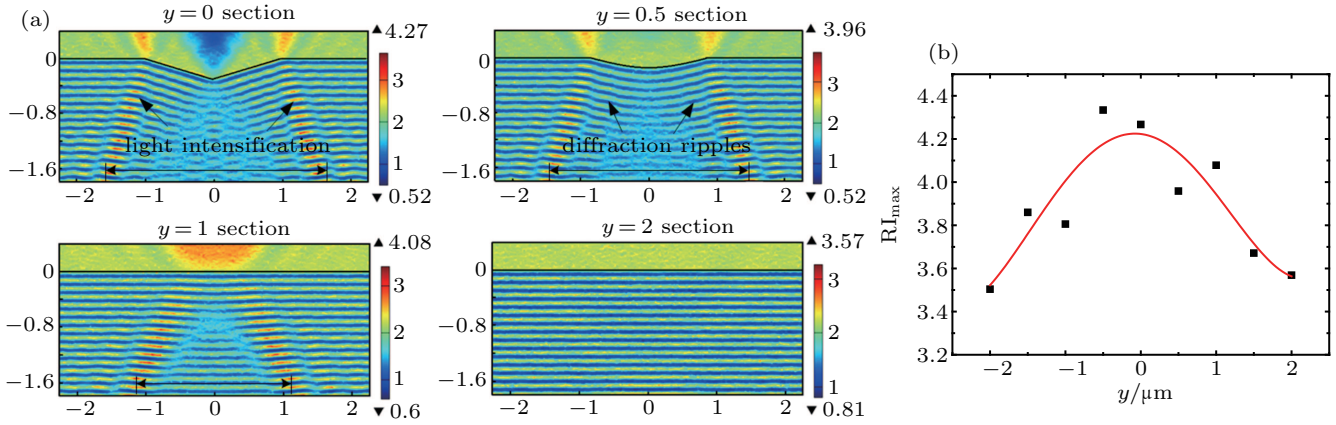


Fig. 6. Relative light intensity distributions on different y-sections of repaired site with a cone angle of 73.3°. (a) The distributions of relative light intensity on different y-sections. (b) The distributions of maximum relative light intensity on different sections.

region is the annular area around the center, indicating that the weak light intensity region is directly below the conical repaired surface and the light intensification zone is below the two sides of the repaired surface. With the increase of section depth, that is, from $z = -0.2$ μm to $z = -1.2$ μm, the radius of the annular light intensification zone becomes larger and larger. The diffraction ripples around the intensification zone also become more and more obvious. Outside the element, the distribution of relative light intensity on the section of $z = 0.2$ is also annular, and the value in the central region is lower. The reason is that light intensification zone is formed above the repaired surface based on the superposition of the transmitted light on the repaired surface and that on the component surface. While the light transmittance close to the center of repaired surface is lower.

Figure 6(a) shows the relative light intensity distributions on the sections of $y = 0$ μm, 0.5 μm, 1 μm, and 2 μm, respectively. It can be seen from the section of $y = 0$ μm that due to the change of the reflected wave propagation direction on the repaired surface, the light intensity inside the element is distorted after light is reflected into the bulk. The reflected light interacts with the incident light to form a light intensification region with a symmetrical distribution of $x = 0$. The maximum relative light intensity on the section is 4.27, which is located at the coordinates of (1.4 μm, −1.25 μm). At the same time, due to the interference of the incident light and the reflected light inside the element, the obvious interference ripples are formed, that is, the standing wave. The transmitted wave is distorted in the air layer, so that two light intensification regions with $x = 0$ symmetry are generated on both sides above

the repaired surface. An obvious weak light intensity shadow is in the center, and a slight diffraction phenomenon can be observed around the intensification zone. From the relative light intensity distributions on the sections of $y = 0.5$ μm, 1 μm, and 2 μm, it can be seen that as the section is far from the center of the repaired site, that is, the repaired contour becomes shallower, the interference ripples inside the element will be weaker. Then, the width of the light intensification zone becomes narrower, the areas of the light intensification region and weak light intensity shadow in the air layer gradually decrease.

Figure 6(b) shows that the distribution of maximum relative light intensity on different sections is approximately parabolic. The maximum relative light intensity on the section of $y = 0$ is the largest. However, there are some fluctuations for the maximum relative light intensity on the sections away from the center, indicating that the effect of the conical repaired site on laser modulation has a typical three-dimensional asymmetric characteristic. It is not accurate to analyze the distribution of light intensity with a simple two-dimensional model, so the 3D models are used in this work to better explore these characteristics.

3.3. Light intensity analysis of repaired sites with different cone angles

Based on the above 3D light intensity analysis of conical repaired site with the cone angle of 73.3°, the diameter D of repaired site is kept always at 2 μm, the depth h is increased from 0.3 μm to 0.72 μm with the interval of 0.02 μm. That is, the cone angle α is decreased from 73.3° to 54.2°, the 3D light intensity of repaired sites with different cone angles is studied by the FEM calculation, and the results are shown in Figs. 7 and 8.

It can be seen from Fig. 7 that as the cone angle of the repaired site decreases, the distortion region caused by the reflected light inside the element becomes wider, and the distribution of relative light intensity is severe disturbance as shown in Fig. 7(d). At the same time, the light intensification in the air layer above the repaired surface becomes more obvious. When the cone angle of the repaired site is 55°, a light intensification zone appears at the interface between the air layer and the repaired surface, which makes the laser induced damage occur easily at the surface of the repaired site.

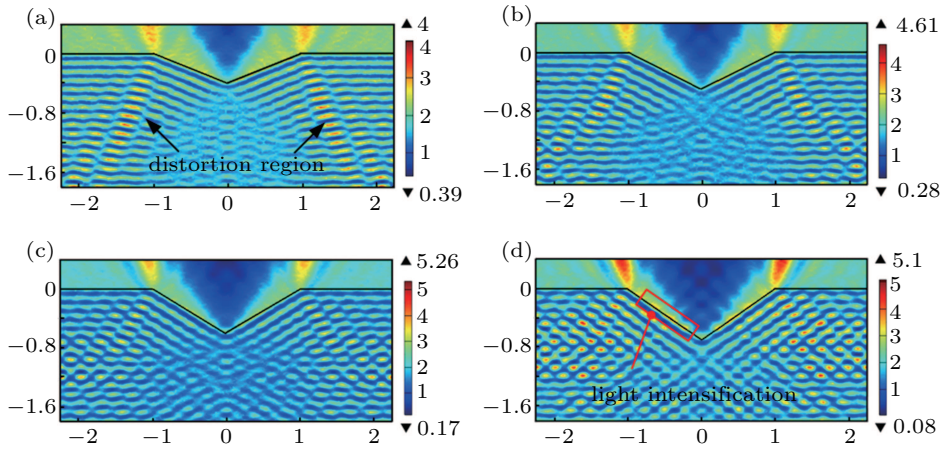


Fig. 7. Relative light intensity distributions on $y = 0$ sections of repaired sites with different cone angles: (a) $\alpha = 68.2°$; (b) $\alpha = 63.4°$; (c) $\alpha = 59°$; (d) $\alpha = 55°$.

It can be seen from Fig. 8(a) that as the cone angle of the repaired site decreases, the maximum relative light intensity inside the element increases continuously, and the effect of the repaired surface on light modulation becomes stronger. The reason is that with the reduction of the repaired angle, the reflectance of light on repaired surface increases while the transmittance decreases, resulting in an increasingly stronger light distortion inside the element. When the cone angle is smaller, most of the incident light energy on repaired surface is reflected back to the inside, so the maximum relative light intensity inside the element increases significantly. When the cone angle is reduced to 55°, the maximum relative light intensity is close to 7, which causes new damage on fused silica surface easily.

Figure 8(b) shows that the positions where the maximum relative light intensities appear are randomly distributed in space. That is, the light intensification region does not appear on a fixed section, but may be distributed at any position around the conical repaired site. The light intensity distribution around the repaired site has a typical three-dimensional feature. This conclusion can also be obtained from Figs. 8(c) and 8(d). Although the maximum relative light intensities on the sections of $y = 0$ and $x = 0$ both decrease with the increase of repaired angle, the variation trends of them are significantly different.

From the above analysis of the relative light intensity dis-

tributions of repaired sites with different cone angles, when the diameter of the repaired site is constant, the effect of the repaired surface on light modulation becomes stronger with the increase of cone angle. It causes the local energy accumulation inside the element, and reduces the laser damage threshold of the fused silica optics. Therefore, in the process of laser repairing surface damage of fused silica by RAM, a larger diameter of the repaired site should be selected as much as possible to increase the cone angle of repaired surface when the depth of repaired site is known, thereby improving the laser damage resistance of fused silica optics. However, the larger repaired area will affect the laser transmittance and the number of repairable damage pits, as shown in Fig. 3. Thus, the selection of the repaired cone angle is very important.

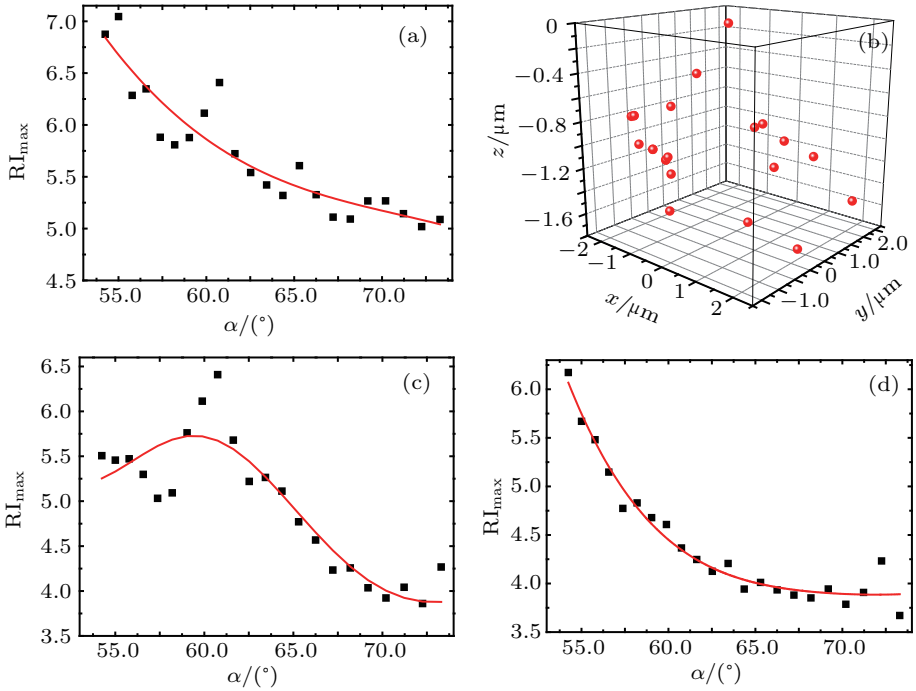


Fig. 8. Relative light intensity distributions inside the element of repaired sites with different cone angles: (a) maximum relative light intensity inside the element; (b) position distributions of maximum relative light intensity; (c) maximum relative light intensity on the section of $y = 0$; (d) maximum relative light intensity on the section of $x = 0$.

3.4. Light intensity analysis of repaired sites with the same cone angle and different sizes

The 3D light intensities of repaired sites with different sizes and the same cone angle of 73.3° are studied by FEM calculation. Figure 9 shows the distributions of calculated relative light intensity on the sections of $z = -1$ μm. It can be seen that with the increase of repaired size, the distributions of relative light intensity on the sections of $z = -1$ μm are similar. The maximum relative light intensity increases slowly, and the radius of the annular intensification area becomes larger and larger. That is, the distortion region caused by the reflected light inside the element becomes wider, the diffraction ripples around the intensification region become more and more obvious, and the diffraction area becomes larger and larger. The distributions of maximum relative light intensity inside each repaired element are shown in Fig. 10.

It can be seen from Fig. 10(a) that as the size of the repaired site increases, the maximum relative light intensity inside the element increases, while the variation trends for different sizes are different. When the depth h of repaired site is less than 0.45 μm, the maximum relative light intensity increases slightly, all of which are within the range of 5.0–5.5. The reason is that the reflected and transmissive ratios of light on repaired surface with same cone angle are consistent. Therefore, the superposition of reflected light and incident light inside the element is similar. The effect of the repaired site size on light intensity is not obvious in a certain range. When the depth h of the repaired site is greater than 0.45 μm, the maximum relative light intensity increases sharply, that is, a large-size repaired site is more likely to cause laser damage. The maximum relative light intensities on the sections of $x = 0$ and $y = 0$ shown in Fig. 10(a) also have similar trends, but their values are significantly different.

Figure 10(b) shows that the positions where the maximum relative light intensity appears are also randomly distributed in space and have typical three-dimensional characteristics, similar to Fig. 8.

According to the above analysis, in order to improve the laser damage resistance of the fused silica optics, a repaired site with larger cone angle should be selected as far as possible

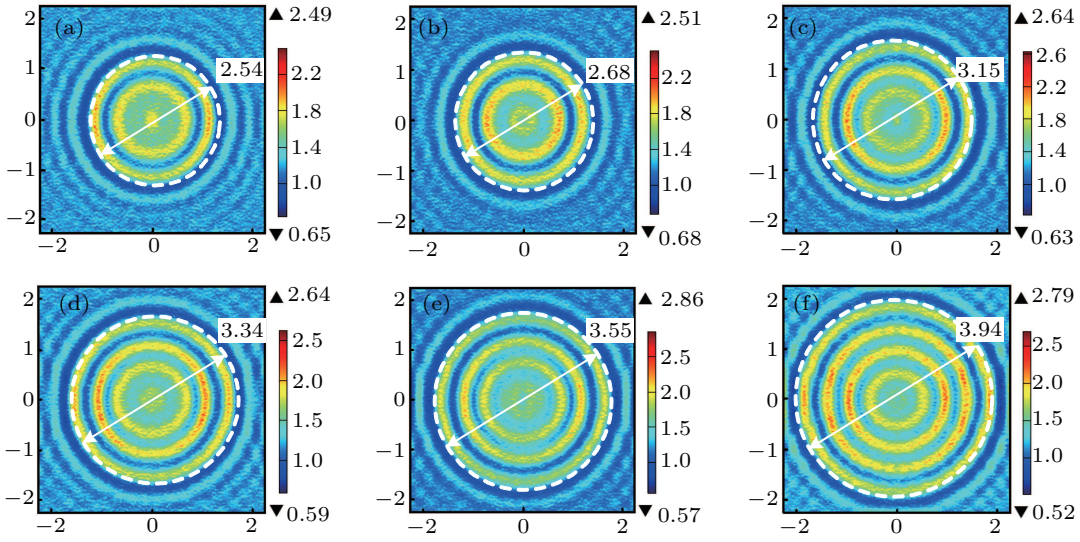


Fig. 9. Relative light intensity distributions on the sections of $z = -1$ μm of conical repaired sites with different sizes: (a) $h = 0.3$ μm; (b) $h = 0.33$ μm; (c) $h = 0.39$ μm; (d) $h = 0.42$ μm; (e) $h = 0.45$ μm; (f) $h = 0.51$ μm.

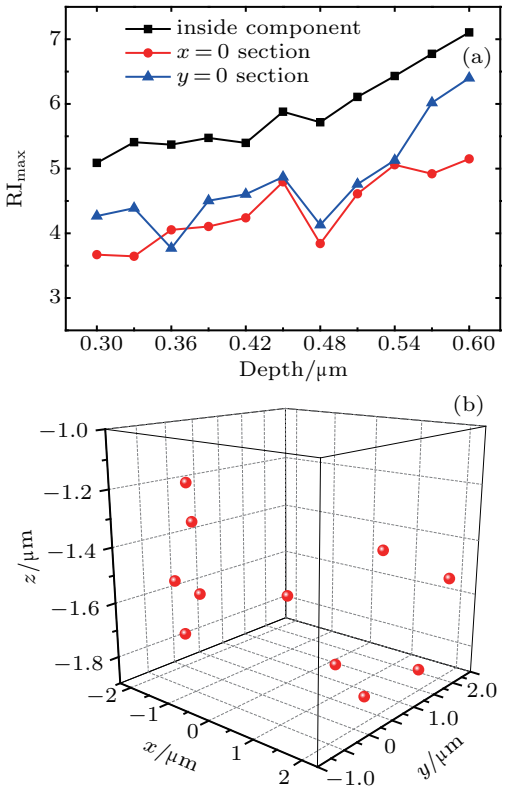


Fig. 10. Relative light intensity distributions inside the element with repaired sites of different sizes: (a) maximum relative light intensity inside the element and that on the sections of $x = 0$ and $y = 0$; (b) position distributions of the maximum relative light intensity appearing inside the element.

under the premise of completely removing the damage pit and surrounding cracks. It is also necessary to ensure that the lateral size of the repaired site will not have an effect on the laser damage threshold of the optics. The practical application shows that by using a suitable repair process, the damage pits on the surface of the fused silica optics can be removed by CO_2 laser RAM method to obtain a conical repaired morphology with a certain cone angle, which can greatly improve the laser damage resistance and extend the service life of the optics. Figure 11 shows a three-dimensional topography of repaired site with cone angle of 12° measured by VHX 1000E super depth of field 3D microscope.

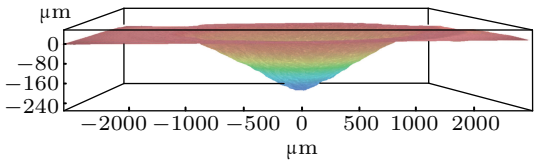


Fig. 11. 3D morphology of conical repaired site with cone angle of 12°.

4. Conclusions

In this work, the finite element mathematical model of 351 nm laser irradiating fused silica optics was established based on the Maxwell electromagnetic field equations. Firstly, the light intensity distributions of array cracks and rectangular repaired contour on fused silica surface are analyzed. The results are consistent with the calculation results of the FDTD method in literature. Then, the FEM model is used to carry out a three-dimensional numerical simulation of near-field light intensity inside fused silica optics with conical repaired site on its surface. The light intensity distribution around the repaired site is studied, also the influences of the cone angle and the size of the repaired site on optical modulation are analyzed. The research shows that for the repaired site with a cone angle of 73.3°, the light intensity distribution inside and outside the element has obvious three-dimensional characteristics. The maximum relative light intensity is 4.77. The relative light intensity on z-section has a circular distribution, and the radius of the annular intensification zone increases with the decrease of z. The distribution of maximum relative light intensity on y-section is parabolically with the increase of y. As the cone an-

gle of the repaired site decreases, the effect of the repaired surface on light modulation becomes stronger, leading to a weak resistance to laser damage. Moreover, the large size repaired site would also reduce the laser damage threshold. Therefore, a repaired site with the larger cone angle and smaller size are preferred in practical localized CO_2 laser repairing of surface damage.

References

[1] Negres R A, Abdulla G M, Cross D A, Liao Z M and Carr C W 2012 *Opt. Express* **20** 13030
[2] Negres R A, Norton M A, Cross D A and Carr C W 2010 *Opt. Express* **18** 19966
[3] Spaeth M, Wegner P, Suratwala T *et al.* 2016 *Fusion. Sci. Technol.* **69** 265
[4] Mendez E, Nowak K, Baker H, Villarreal F and Hall D 2006 *Appl. Opt.* **45** 5358
[5] Yang S T, Matthews M J, Elhadj S, Cooke D, Guss G M, Draggoo V G and Wegner P J 2010 *Appl. Opt.* **49** 2606
[6] Cormont P, Bourgeade A, Cavaro S, Donval T, Doualle T, Gaborit G, Gallais L, Lamaignere L and Rullier J L 2015 *Adv. Eng. Mater* **17** 253
[7] Cormont P, Combis P, Gallais L, Hecquet C, Lamaignère L and Rullier J L 2013 *Opt. Express* **21** 28272
[8] Palmier S, Gallais L, Commandré M, Cormont P, Courchinoux R, Lamaignère L, Rullier J L and Legros P 2009 *Appl. Surf. Sci.* **255** 5532
[9] Matthews M J, Yang S T, Shen N, Elhadj S, Raman R N, Guss G, Bass I L, Nostrand M C and Wegner P J 2015 *Adv. Eng. Mater* **17** 247
[10] Dai W, Xiang X, Jiang Y, Wang H J, Li X B, Yuan X D, Zheng W G, Lv H B and Zu X T 2011 *Opt. Lasers Eng.* **49** 273
[11] Gallais L, Cormont P and Rullier J L 2009 *Opt. Express* **17** 23488
[12] Gao X, Jiang Y, Qiu R, Zhou Q, Zuo R, Zhou G R and Yao K 2017 *Opt. Mater* **64** 295
[13] Li L, Xiang X, Zu X T, Yuan X D, He S B, Jiang X D and Zhao W G 2012 *Chin. Phys. B* **21** 044212
[14] Bass I L, Guss G M, Nostrand M J and Wegner P J 2010 *Proc. SPIE* **7842** 784220
[15] Doualle T, Gallais L, Monneret S, Bouillet S, Bourgeade A, Ameil C, Lamaignère L and Cormont P 2016 *Opt. Eng.* **56** 011022
[16] Zhang C C, Zhang L J, Jiang X D, Jia B S, Liao W, Dai R C, Chen J, Yuan X D and Jiang X D 2020 *Opt. Lasers Eng.* **125** 105857
[17] Folta J, Nostrand M, Honig J et al 2013 *Proc. SPIE* **8885** 88850Z-2
[18] Doualle T, Gallais L, Monneret S, Bouillet S, Bourgeade A, Ameil C, Lamaignére L and Cormont P 2016 *Proc. SPIE* **10014** 1001407
[19] Zheng W G, Wei X F, Zhu Q H, Jing F, Hu D X, Su J Q, Zheng K X, Yuan X D, Zhou H and Dai W J 2016 *High. Power. Laser. Sci.* **4** e21
[20] Matthews M J, Bass I L, Guss G M, Widmayer C C and Ravizza F L 2008 *Proc. SPIE* **6720** 67200A
[21] Adams J, Bolourchi M, Bude J, Guss G M, Matthews M and Nostrand M 2010 *Proc. SPIE* **7842** 784223
[22] Zhang C L, Yao C M and Wang C D 2016 *Optik* **127** 3750
[23] Zhang C L, Yao C M and Wang C D 2016 *Optik* **127** 3105
[24] Fang Z, Zhao Y A, Chen S, Sun W and Shao J 2013 *Appl. Opt.* **52** 7186
[25] Li B, Zhou Q Y, Jiang Y, Xiang X, Liao W, Jiang X L, Wang H J, Luan X Y, Zheng W G and Yuan X D 2017 *Opt. Eng.* **56** 016113
[26] Yang L, Xiang X, Miao X X, Li L, Yuan X D, Yan Z H, Zhou G R, Lv H B, Zheng W G and Zu X T 2016 *Chin. Phys. B* **25** 014210
[27] Xie Y X, Qi L, Liu Y L and Zhang R Z 2019 *Optik* **184** 220