Numerical simulation of the modulation to incident laser by the repaired damage site in a fused silica subsurface*

Li Li(李 莉)[a], Xiang Xia(向 霞)[a)b)], Zu Xiao-Tao(祖小涛)[a)†],
Wang Hai-Jun(王海军)[b)], Yuan Xiao-Dong(袁晓东)[b)], Jiang Xiao-Dong(蒋晓东)[b)],
Zheng Wan-Guo(郑万国)[b)], and Dai Wei(戴 威)[b)]

[a)] *Institute of Physics and Electronics, University of Electronic Science and Technology of China, Chengdu* 610054, *China*
[b)] *Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang* 621900, *China*

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One of the main factors of laser induced damage is the modulation to incident laser which is caused by the defect in the subsurface of the fused silica. In this work, the repaired damage site irradiated by CO_2 laser is simplified to a Gaussian rotation according to the corresponding experimental results. Then, the three-dimensional finite-difference time-domain method is employed to simulate the electric field intensity distribution in the vicinity of this kind of defect in fused silica front subsurface. The simulated results show that the modulation is notable, the E_{max} is about 2.6 times the irradiated electric field intensity in the fused silica with the damage site (the width is 1.5 μm and depth is 2.3 μm) though the damage site is repaired by CO_2 laser. The phenomenon and the theoretical result of the annular laser enhancement existed on the rear surface are first verified effectively, which agrees well with the corresponding experimental results. The relations between the maximal electric field intensity in fused silica with defect depth and width are given respectively. Meanwhile, the corresponding physical mechanism is analysed theoretically in detail.

Keywords: laser-induced damage, fused silica, repaired damage site, three-dimensional finite-difference time-domain

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1. Introduction

For the laser used in inertial confinement fusion, the useful output of high power lasers has been limited for the last five decades by the laser induced damage of optical components.[1,2] So far, the resistance against surface damage is still a critical technological challenge, particularly at 355 nm.[3–6] One of the fundamental mechanisms has been proposed, which is the role of defects on the initiation and the growth of laser induced damage. There is a potential effect that the modulation to incident laser is caused by the defects in the subsurface of the fused silica in the effect of defects on laser induced damage.[7,8]

There have been some reports about the modulation of defects to incident laser. Génin *et al.* has numerically simulated the intensity distribution by using the TEMPEST code around the plannar and conical cracks.[3] Bonneau *et al.* has performed two-dimensional (2D) simulation of intensity distribution around the plannar and conical cracks by using the DELPOR code and HESIONE code.[9] Hua *et al.* simulated the light intensity distribution in the vicinity of 3D Hertzian conical scratches on fused silica subsurface.[10] Nevertheless, these simulations focus on the given kinds of cracks which are plannar and conical cracks.

In order to avoid damage site growth during 355 nm irradiation, one of the most promising methods is to utilize a CO_2 laser operating at a 10.6-μm wavelength to locally melt and evapourate the silica surface by producing typically smooth, Gaussian shaped pits.[11,12] However, it has been observed that after 355 nm irradiation of a zone which has received CO_2 laser treatment, new damages always occur in the surrounding area of the crater, even when the surface is free from any other visible defects or silica re-deposition.[13] Gallais investigated the residual stress field created near the mitigated sites and its influence on the efficiency of the CO_2 laser mitigation of damage growth process and developed a numerical model taking into account laser energy ab-

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†Corresponding author. E-mail: xtzu@uestc.edu.cn
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sorption, heat transfer, thermally-induced stress and birefringence.[13] However, they did not consider the modulation of the damage site to incident laser.

In this work, we simplified the damage site to a Gaussian rotation. The 3D finite-difference time-domain method is developed to solve Maxwell equations. Then, the electric field intensity distribution in the vicinity of repaired defect site in the front subsurface of fused silica is numerically simulated for the first time. The relationships between the maximal electric field intensity in fused silica and defect geometry are given. This work aims at providing the theoretical direction about the safe geometry of damage site during inertial confinement fusion.

2. Model and method

Figure 1(a) shows the micrograph of a typical damage site in the fused silica surface induced by 3ω (355 nm) laser irradiation at fluence corresponding to inertial confinement fusion experiments. Figure 1(b) is the micrograph of the defect site after CO_2 laser repairing. As can be seen, the surface of the repaired site shown in Fig. 1(b) is much smoother than that in Fig. 1(a). Figure 2 is the stylus profilometry trace of the repaired site shown in Fig. 1(b). Based on the morphologies in Fig. 1(b) and Fig. 2, we simply repaired pit to a mathematics model with an absolute smooth surface.

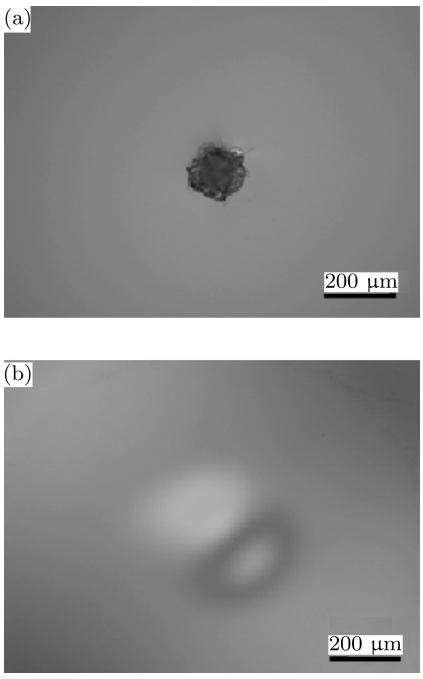


Fig. 1. Microscopic images of defect site: (a) before CO_2 laser irradiation; (b) after irradiation.

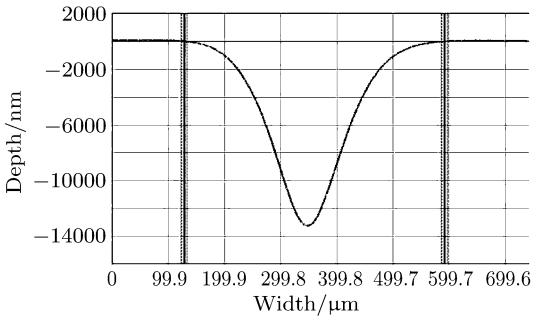


Fig. 2. Stylus trace through the pit shown in Fig. 1(b).

As can be seen from Fig. 2, the curve in Gauss shape shows that the pit profile satisfies Gaussian distribution. So we regard the repaired pit as a Gaussian rotation which can be described by the 3D equation

$$z = z_0 + A\exp\{-2[(x-x_0)^2 + (y-y_0)^2]/w^2\},$$

where xoy plane parallels the fused silica surface, (x_0, y_0, z_0) is the position of the repaired pit bottom. The A and W are the parameters controlling the Gaussian rotation shape. The A controls the defect depth and W controls the defect width. According to the above equation, the 3D geometry is plotted in Fig. 3 with the bottom position (0, 0, 0) by using MATLAB.

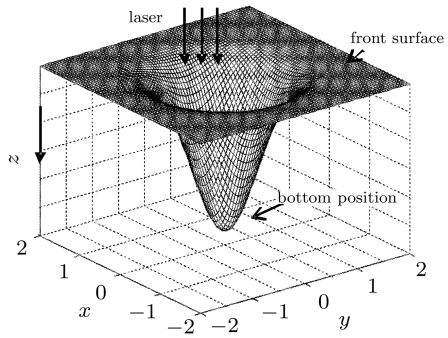


Fig. 3. The 3D schematic diagram of the repaired pit.

Maxwell's equations are solved by the 3D finite-difference time-domain method to calculate the electric field intensity distribution in the vicinity of a repaired damage site.[14,15] During the numerical calculation, the perfectly matched layer boundary condition is adopted.[15] The different grid size is $\delta = \lambda/12 = 29.25$ nm. The whole calculation domain is $(138\delta, 298\delta, 168\delta)$. The relative dielectric constant ε_r of fused silica is 2.25. The 3ω laser with the amplitude of 1.0 V/m travels in the direction normal to the surface, namely alone z-axis. The TM wave is considered in this work. Other defects in the fused silica are ignored. It is assumed that the repaired defect site is on

the front surface and the defect is empty ($\varepsilon_{\rm r} = 1.0$). In simulation, the size of the defect site is about 10 percent of the actual one.

3. Results and discussion

At first, the electric field distribution in the vicinity of a given repaired damage site is calculated (see Fig. 4). The parameters A and W are 40δ and 30δ, respectively. From Fig. 4, we can see that the distribution of electric field in fused silica is symmetrical and the modulation of electric field is notable. Specially, the electric field is enhanced in fused silica. Also, there is a scattering domain just behind the defect. This phenomenon can be analysed as follows. Firstly, since the defect is empty ($\varepsilon_{\rm r}$ equals 1.0 which is less than that of fused silica), it seems that a concave mirror is laid at the position of the damage site. The incident laser is scattered by the concave mirror. So the scattering domain comes into being behind the defect. Secondly, the scattering wave overlaps with the incident wave in fused silica. As they satisfy the conditions of interference to reinforce in the overlap, the electric field is enhanced.[16]

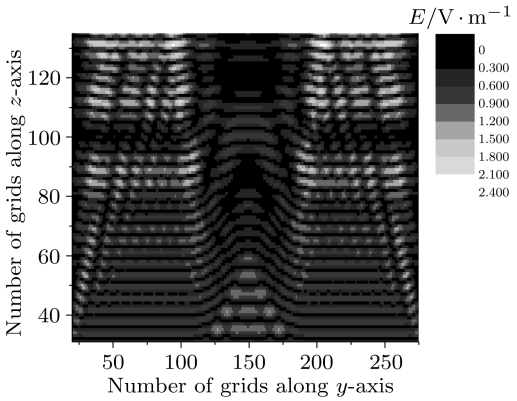


Fig. 4. Electric field distribution E in yoz plane as $x = 70\delta$.

From the calculated data of Fig. 4, it is found that, though the defect is in the front surface, the maximal electric field appears in the vicinity of the rear surface ($z = 135\delta$). Crisp *et al.*[17] has carefully observed and analysed the rear surface damage by Fresnel reflections for normal incidence. They reported that a field distribution is set up such that the electric field at the front surface is 0.8 V/m and the electric field at the rear surface is 0.96 V/m. However, their theoretical results are for the fused silica without any defect. In this work, as the case that there is a defect in the fused silica surface, the analyses of Crisp *et al.*[17] is applicable too. The difference is that the enhancement of electric field intensity on the rear surface is more evident than the case without any defect for the scattering of the defect. According to the calculated result in Fig. 4, the maximal electric field is 2.0374 V/m, at $x = 70\delta$, $y = 205\delta$, $z = 131\delta$. In order to illustrate the electric field enhancement more clearly, we plot the electric field distribution in xoy plane at $z = 135\delta$ in Fig. 5. From Fig. 5, we can see the distinct electric field enhanced loops. We also obtained the same result in experiment. Figure 6 shows the experimental result at the same investigation condition.

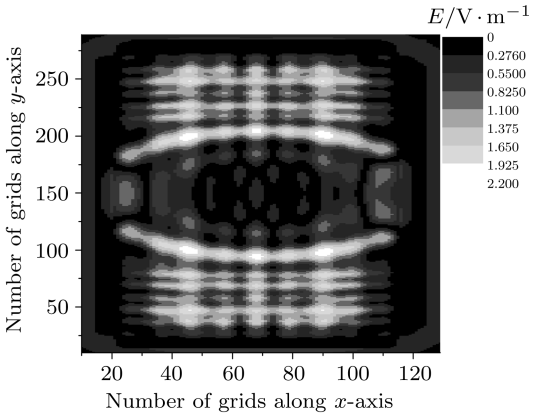


Fig. 5. Electric field distribution in xoy plane for $z = 135\delta$.

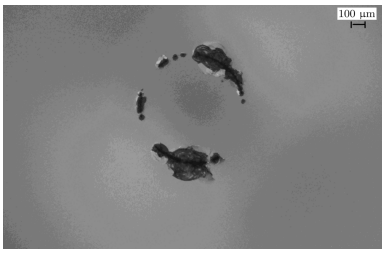


Fig. 6. Micrograph of rear surface damage.

Figure 7 shows the electric field evolution with y for a given x (70δ) at two different z values in Fig. 5. From Fig. 7, it can be seen that the distribution of the electric field is symmetrical. The peak values of the electric field appear nearby $y = 100\delta$ and 185δ. These characteristics of Fig. 7 are coincident with Fig. 5. According to Figs. 5 and 7, we can deduce that, once the electric field on the loop is higher than the electric damage threshold, the loop is damaged first and then outside the loop and at last inside the loop. In Fig. 5, the loop overflows the figure, the reason is that the diameter of enhanced loop is already greater than the calculated domain along x direction.

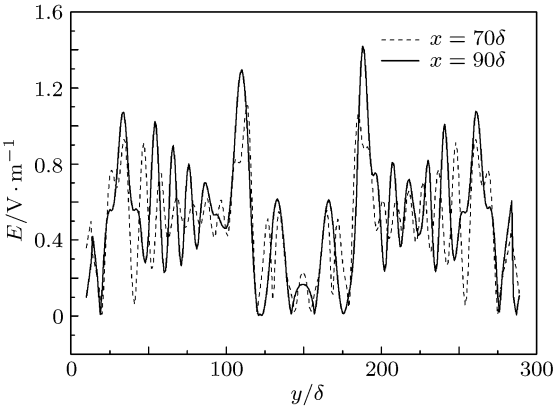


Fig. 7. Evolution of electric field with y at given x and z.

In the actual mechanical process of fused silica, the width and depth of defects vary in a large range from several nm to several μm, so it is necessary to discuss the role of the width and depth played in the modulation to the electric field. The variations of the maximum electric field $E_{\max}$ in fused silica with the depth of the repaired damage sites are shown in Fig. 8.

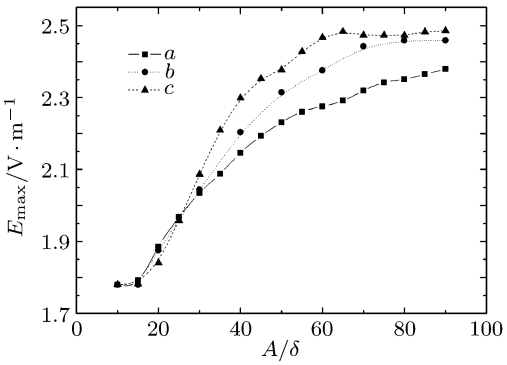


Fig. 8. Variation of $E_{\max}$ with defect depth. Curves a, b, and c are simulated at three cases that the width equals 20δ, 30δ and 40δ, respectively.

From Fig. 8, it can be seen that, for $A < 25\delta$, the three curves almost overlap, especially for $A < 15\delta$; for $A > 25\delta$, the gaps appear between the curves. With the increasing A, the gaps become larger. As $A > 80\delta$, the gaps seem to be constant. As for one curve, such as curve b, it remains a constant which is 1.78 V/m till $A = 15\delta$. Then, the curve ascends with A. Meanwhile, the ascending speed gradually becomes slower. As $A > 80\delta$, it approaches a constant of about 2.45 V/m. The phenomena illuminate that the effect of the depth of the repaired damage site on electric field modulation is slender for $A < 15\delta$ and $A > 80\delta$, while the effect is significant for $25\delta < A < 80\delta$.

Next, we investigate the effect of the repaired damage site width on modulation (see Fig. 9). It can be seen that the variations of the three curves with width are similar. For $W < 30\delta$ and $W > 55\delta$, the three curves almost overlap; for $30\delta < W < 55\delta$, the gaps between them appear, but they increase in the same trend. The peak values of $E_{\max}$ all appear at $W = 50\delta$, which are 2.51 V/m, 2.59 V/m and 2.64 V/m for curves a, b and c, respectively. As for one curve, for example curve b, it ascends slowly for $W < 30\delta$. Once $W > 30\delta$, it hoicks rapidly. For $30\delta < A < 55\delta$, it rises with some fluctuation and sharply drops for $W > 55\delta$. From the above phenomena, we can deduce that the effect of the width of the repaired damage site on electric field modulation is evident for $30\delta < W < 55\delta$, while the effect can be ignored for $W < 30\delta$ and $A > 55\delta$.

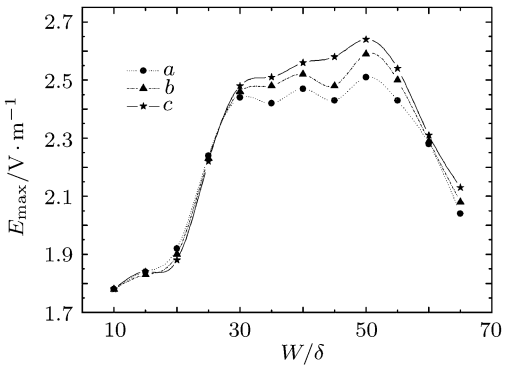


Fig. 9. Variation of $E_{\max}$ with defect width. Curves a, b, and c are simulated at three depths 70δ, 75δ and 80δ, respectively.

So far, we have discussed the effect of the geometry of the repaired damage site on the modulation to electric field distribution in fused silica.

4. Conclusions

The modulation of the Gaussian defect site repaired by CO_2 laser to 3ω laser is investigated in detail. The simulation results show that the defect site does modulate the irradiated electric field in a high degree. Some conclusions are as follows:

1) Under the investigation condition of this work, the enhancement of electric field intensity on the rear surface damage is obvious. There are enhancement loops on the rear surface of fused silica. The electric field inside the loop is weaker, while the electric field on and outside the loop is relatively strong.

2) The effects of defect site geometry on modulation are that the modulation is small at different depths (less than 20δ and more than 80δ) for a given width, while the modulation is significant at different widths for a given depth as the width is between 30δ

and 55δ (the peak value of $E_{\max}$ is about 2.45 V/m). As for the defect site width, the modulation first rises and then decline, the peak value appears within the width between 20δ and 50δ.

Therefore, we should avoid the defect for $A > 20\delta$ and $30\delta < W < 55\delta$ in the laser facula during experimental and actual inertial confinement fusion optical path.

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