

Hydrofluoric acid-based etching effect on the surface pit, crack, scratch, and laser damage site of fused silica optics

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Abstract

Large-scale, high-power laser facilities currently serve as the foundation for inertial confinement fusion (ICF) research. In these facilities, fused silica optics play an irreplaceable role in delivering extremely high-intensity ultraviolet lasers to fusion targets. However, surface fractures on the optics—including surface pits, cracks, scratches, and laser damage sites—degrade the beam quality of transmitted lasers, reduce laser damage resistance, shorten the optics' lifetime, and consequently limit the output performance of the laser facility. In this work, to mitigate surface fractures, the effects of hydrofluoric acid-based (HF-based) etching on these fractures are investigated both experimentally and theoretically. Experimental results of three-dimensional (3D) morphological evolution of surface fractures demonstrate that the fractures become passivated and their profiles smoothed after etching, indicating that HF-based etching is a promising approach for improving the local surface quality of fractures. Notably, it is found that HF-based etching can significantly suppress laser damage growth at damage sites by mitigating both surface and subsurface fractures, thus representing a promising wet chemical method for repairing laser-induced damage optics. In the theoretical study, an explicit local-curvature-dependent etching model is proposed. Based on this model, finite difference time domain (FDTD) simulation results show excellent agreement with experimental results, revealing the detailed physical processes of HF-based etching. It is demonstrated that FDTD simulation can serve as a reliable and efficient method for predicting the morphological evolution of surface fractures during etching.

Full Text

Preamble

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Abstract

Large-scale, high-power laser facilities serve as the foundation for inertial confinement fusion (ICF) research. In these facilities, fused silica optics play an irreplaceable role in delivering extremely high-intensity ultraviolet laser radiation to fusion targets. However, surface fractures—including pits, cracks, scratches, and laser damage sites—degrade the beam quality of transmitted laser light, reduce laser damage resistance, shorten optics lifetime, and ultimately limit the output performance of laser facilities. In this work, we experimentally and theoretically investigate hydrofluoric acid-based (HF-based) etching as a method to mitigate these surface fractures. Experimental results tracking three-dimensional (3D) morphological evolution demonstrate that HF-based etching passivates surface fractures and smooths their profiles, proving to be a promising approach for improving local surface quality. Notably, HF-based etching significantly suppresses laser damage growth at damage sites by mitigating both surface and subsurface fractures, establishing it as a promising wet chemical method for repairing laser-induced damage. The theoretical component of this study introduces an explicit local-curvature-dependent etching model. Finite difference time domain (FDTD) simulations based on this model show excellent agreement with experimental results, revealing the detailed physical processes underlying HF-based etching and demonstrating that FDTD simulation can serve as a reliable and efficient tool for predicting the morphological evolution of surface fractures during etching.

Keywords: fused silica; HF-based etching; surface fracture; morphological evolution; finite difference simulation

1. INTRODUCTION

Large-scale, high-power laser facilities—including the National Ignition Facility in the United States, the SG series laser facility in China, the Laser Megajoule Facility in France, the Iskra-6 facility in Russia, and the Extreme Light Infrastructure—pioneer research in high-energy-density physics (HEDP). Within HEDP research, laser-driven inertial confinement fusion (ICF) represents a major focus, with the ultimate goal of making fusion energy usable and controllable to meet global energy demands in the coming centuries. Achieving ICF critically depends on the output performance of these large laser facilities, which

demand numerous fused silica optical components with excellent surface quality and high laser damage resistance to withstand extremely intense laser radiation operating near or above their laser-induced surface damage thresholds.

While the intrinsic laser-induced surface damage threshold of fused silica optics exceeds 100 J/cm^2 , these optics typically exhibit laser damage when exposed to 351 nm, 3 ns laser pulses at fluences of 5–15 J/cm^2 , depending on surface finishing and post-processing conditions. At fluences below 10 J/cm^2 , surface fractures are believed to be the most common native laser damage precursors. These fractures—including pits, cracks, scratches, and pre-existing laser damage sites—degrade transmitted laser beam quality, reduce damage resistance, shorten component lifetime, and severely limit facility performance. Figure 1 [Figure 1: see original paper] illustrates examples of micron-sized surface fractures with complex morphology observed on fused silica optics after routine use. Such fractures prove pernicious under intense laser irradiation, jeopardizing expensive optics and hindering facility operations. Therefore, mitigating surface fractures is imperative.

Two primary approaches exist for mitigating surface fractures. The first involves “dry physical etching” methods such as ion beam etching, reactive ion beam etching, ultra-fine surface finishing, and laser polishing. However, these dry methods suffer from low efficiency when processing meter-scale optics in industrial settings. The second, more efficient approach employs “wet chemical etching” using hydrofluoric (HF) acid-based solutions. Historically, Scheele first prepared HF acid in 1771 and likely discovered its ability to etch silicate glasses. Over fifty years later, Berzelius identified the reaction products between SiO_2 and HF as tetrafluorosilane and water. Today, the overall chemical reaction of SiO_2 in dilute HF solution is summarized as: solid $2\text{H}_2\text{O}$.

In aqueous solutions with higher HF concentrations, the solution contains H^+ , F^- , HF, 2HF , and $2\text{H}_2\text{F}^+$ species, as HF is a weak acid that does not fully dissociate. The equilibrium constants between these species at 25°C are: $[\text{H}^+][\text{F}^-]/[\text{HF}] = 6.85 \times 10^{-4} \text{ mol/L}$, $[\text{HF}_2^-]/([\text{HF}][\text{F}^-]) = 3.963 \times 10^{-1} \text{ L/mol}$, and $[\text{H}_2\text{F}_2]/[\text{HF}] = 2.7 \text{ L/mol}$. These chemical reactions enable surface fractures to dissolve in HF-based solutions.

HF-based etching has been shown to improve the laser damage resistance of fused silica optical surfaces. This wet chemical etching method efficiently produces meter-scale optics with high laser damage resistance and has been patented. Recent developments have utilized HF/ HNO_3 or KOH as etchants, demonstrating significant improvements in both laser damage resistance and surface quality. Nevertheless, the detailed morphological evolution of surface fractures during HF-based etching—which underlies these improvements—remains poorly understood. Two main factors contribute to this knowledge gap: the difficulty and danger of in situ tracking fracture evolution during immersion in HF solution, and the complex, incompletely understood etching mechanism and reaction kinetics of silica glass dissolution. To address this, Wong et al. and Feit et al. from Lawrence Livermore National Laboratory

pioneered finite difference simulations of the etching process.

Building upon this foundation, our work presents both experimental and theoretical studies of surface fracture morphological evolution during HF-based etching. We propose a local-curvature-dependent etching model and present both simulation and experimental results. This paper is organized as follows: Section 2 details the experimental procedures for HF-based wet chemical etching, Section 3 presents the analytical etching model and FDTD simulations, Section 4 compares and discusses experimental and simulation results, and Section 5 summarizes the work.

2. EXPERIMENTAL

To track morphological evolution, we used round fused silica samples (type D160, Languang Optical Technology Co., Ltd, China) with a density of 2.24 g/cm^3 , diameter of 50.0 mm, and thickness of 5.0 mm. Several pits were indented on the sample surface using a hardness tester (LAIHUA HVT-1000A) with loads ranging from 0.098 to 2.94 N. Micron-deep surface cracks and millimeter-long surface scratches were present on the initial sample surface. Laser damage sites were generated using 355 nm, 6.3 ns laser pulses at $\sim 15 \text{ J/cm}^2$ fluence. A buffered HF-based solution was prepared with 2.4% HF, 12.0% NH_4F , and 85.6% ultrapure water by weight fraction.

The initial sample was immersed in the HF-based solution for 5.0 minutes to remove the surface hydrolysis layer. The etching process then proceeded with successive phases of 0.5, 1.0, 1.0, 1.0, and 2.0 hours, yielding cumulative etching times of 0.5, 1.5, 2.5, 3.5, and 5.5 hours. For surface laser damage sites, the total etching time was 24.0 hours. During etching, megasonic agitation at 1.30 MHz was applied at the bottom of the etchant container. Before each etching phase, the sample was rinsed in pure water with sweeping 40–270 kHz ultrasonic agitation for 30.0 minutes.

All etching experiments were conducted at room temperature ($23.0 \pm 1.0 \text{ }^\circ\text{C}$) and relative humidity of $45 \pm 5\%$. After each etching phase, two-dimensional morphological characterization of the surface fractures was performed using optical microscopy (custom Nikon Inc. system). Three-dimensional profiles were quantitatively measured using atomic force microscopy (AFM, XEI-100, PSIA Inc.) or 3D profilometry.

3. MODELING THE ETCHING PROCESS

This section presents two etching models: isotropic etching and local-curvature-dependent etching. When fused silica optics with surface fractures are submerged in HF-based solution, wet chemical etching is initiated.

Figure 2 [Figure 2: see original paper] illustrates the wet chemical etching system. The central rugged curve represents the surface fractures of submerged fused silica optics, with arrows indicating the etching direction opposite to the

local surface normal vector. When the local surface spatial frequency is low (i.e., sufficiently smooth, as shown in the left half of Fig. 2), etching can be considered isotropic, with uniform etching rates across the surface. However, when spatial frequency is high (i.e., sufficiently rough, as shown in the right half of Fig. 2), etching becomes anisotropic, with rates highly dependent on local curvature. Intuitively, the etching rate at a sharp peak exceeds that at a valley because reaction products diffuse more readily from peaks into the surrounding solution than from valleys.

To model surface fractures, a 3D grid can simulate the surface if sufficiently fine. Figure 3 [Figure 3: see original paper] shows a meshed surface and its top projection onto a fixed ground reference frame. This fixed reference frame remains unchanged during surface variation, preventing numerical divergence in FDTD simulations.

3.1 Isotropic Etching

For a surface point P_0 at time t_0 , after a short etching time δt (at time t_1), it evolves to a new position P_1 . Point P_1 can be considered as originating from P_0 along the opposite direction of the local normal vector \mathbf{n} at point P_0 at time t_0 . The spatial relationship between P_1 and P_0 is:

$$P_1 = P_0 - E(t) \cdot \mathbf{n} \cdot \delta t$$

where $E(t)$ is a time-dependent (but not position-dependent) etching rate. This equation forms the basis for modeling wet chemical etching. In Cartesian coordinates, it decomposes as:

$$x_1 = x_0 - E(t) \cdot \mathbf{n}_x \cdot \delta t \quad y_1 = y_0 - E(t) \cdot \mathbf{n}_y \cdot \delta t \quad z_1 = z_0 - E(t) \cdot \mathbf{n}_z \cdot \delta t$$

Here, x_1 , y_1 , and z_1 are the positional projections of P_1 onto the reference frame, while x_0 , y_0 , and z_0 are those of P_0 . \mathbf{n}_x , \mathbf{n}_y , and \mathbf{n}_z are the directional components of normal vector \mathbf{n} , with $\mathbf{n} = (\mathbf{n}_x, \mathbf{n}_y, \mathbf{n}_z)$. The function $E(t)$ and parameter δt can be set based on experimental results. The following describes determination of the local normal vector.

As shown in Figure 4 [Figure 4: see original paper], for a surface point P with neighboring points A , B , C , and D , the local normal vector at P is determined as:

$$\mathbf{n} = (\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4) / |\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4|$$

where \mathbf{n}_1 , \mathbf{n}_2 , \mathbf{n}_3 , and \mathbf{n}_4 are the unit normal vectors of surfaces PAB , PBC , PCD , and PDA , respectively. Equation (5) can be solved using the finite difference time domain method.

3.2 Local-Curvature-Dependent Etching

When surface fracture spatial frequency is high (i.e., sufficiently rough), wet chemical etching becomes local-curvature-dependent, requiring modification of

the basic equation. For a 3D surface $S(x, y)$, where S represents surface height at position (x, y) , we define:

$$F = S(1 + S_y^2) - 2S S_{yS} y + S_{yy}(1 + S^2) \quad G = (1 + S^2 + S_y^2)^{3/2}$$

The local surface curvature at position (x, y) is then derived as:

$$= F / G$$

This curvature modifies the basic equation through the following relationship between local etching rate and local surface curvature:

$$E_{lc} = E_r \cdot B_d$$

where E_{lc} is the local curvature-dependent etching rate, E_r is the etching rate on an ideal flat surface, and B_d is an adaptive coefficient expressed as:

$$B_d = (x_{max} - x_{min}) \cdot \exp(-mC^2) + x_{min}$$

Here, x_{max} represents the ratio of maximum local-curvature-dependent etching rate (at peaks) to the uniform rate E_r , while x_{min} is the ratio of minimum rate (at valleys) to E_r . In this work, $x_{max} = 2.5$ and $x_{min} = 0.5$, with mC representing variable mean local curvature. Based on these values, Figure 5 [Figure 5: see original paper] illustrates the typical relationship between local etching rate and local surface curvature. The rate changes little (exhibiting isotropic behavior) when curvature varies from -5 to 5 m^{-1} , but changes significantly when curvature approaches -10 m^{-1} (valleys) or 10 m^{-1} (peaks), reaching minimum and maximum values, respectively.

Consequently, the basic equation is modified as:

$$\text{nextP} = P - E_{lc}(t) \cdot n \cdot \delta t$$

where P denotes the current point and nextP denotes its evolved position. The local-curvature-dependent, time-dependent etching rate $E_{lc}(t)$ governs evolution. Surface evolution employs an Euler description relative to a fixed reference frame and grid. An initial surface $S_0(X, Y)$ (described as a matrix) evolves to $S_0'(X, Y)$ after time δt . The normal vector matrix of surface S_0 is $n(X, Y)$. The evolved surface is:

$$S_0'(X, Y) = S_0(X, Y) - E_{lc}(t) \cdot n(X, Y) \cdot \delta t$$

Here, S_0' is the varied S_0 relative to the fixed grid. The minimum reference grid size should exceed twice the etching depth to avoid numerical divergence. In practice, low-pass Fast Fourier Transform filters or convolution can eliminate singularities in surface fractures.

4. RESULTS AND DISCUSSION

This section presents comparative experimental and simulation results, sequentially discussing HF-based etching effects on surface pits, cracks, scratches, and

laser damage sites.

4.1 Mass Removal of Fused Silica Optics During HF-Based Etching

Figure 6 [Figure 6: see original paper] shows the experimental mass removal of the fused silica sample during etching. The black dot-solid line indicates mass change, decreasing linearly with etching time. Red triangles show mass removal relative to initial mass at different etching times, while the blue solid line provides linear fitting. The initial sample mass was 21965.4 ± 0.1 mg, decreasing to 21745.2 ± 0.1 mg after 7.5 hours of etching—a reduction of approximately 1.0%. Correspondingly, sample volume decreased by 1.0% while surface area changed by less than 1.0%. This linear behavior results from the etchant volume being much larger than the sample volume, and fracture surface area being much smaller than the total optics surface area. Mass removal follows the linear equation:

$$M_r = r_m \cdot T$$

where M_r is mass removal, T is etching time in hours, and $r_m = 28.23$ mg/hr is the etching-induced mass removal rate, corresponding to an etching rate of 2.67 m/hr in terms of thickness.

4.2 HF-Based Etching Effect on Surface Pits

Surface pits are common defects that limit laser damage resistance by modulating laser pulse power distribution, making damage likely at pit locations. Understanding their morphological evolution during wet chemical etching is therefore a major concern.

Figure 7 [Figure 7: see original paper] shows the morphological evolution of indented surface pits during etching. Initially, several pits with complex, rough morphology appear on the optics surface (“0.0 h”). Some pits are isolated (marked “1” and “2”) while others are interconnected (marked “3”). The morphological differences between pits “1” and “2” result from varying indenting forces. Pit “1” initially exhibits a diamond-shaped core with six crack tails. During etching, the core and tails enlarge (at 0.5 h and 1.5 h) and eventually blend into a large circular pit with smoothed surface (at 2.5 h, 3.5 h, and 5.5 h). For circular pit “2” , the initially rough surface gradually becomes smooth. Other isolated pits evolve similarly. Interconnected pit “3” also shows surface smoothing during etching. This smoothing effect is a common feature of pit evolution and shows promise for improving laser-induced damage resistance.

Notably, wet chemical etching only slightly enlarges pit size, unlike CO_2 laser treatment, which typically enlarges pits by several times.

To understand the evolution mechanism of a single pit, we numerically modeled a sharp cone-shaped pit (Figure 8 [Figure 8: see original paper], top-left) as an initial morphology for simulation. The pit cusp becomes slicked and the

opening gradually enlarges during etching, with the diameter-to-depth ratio increasing significantly. Overall, pit morphology becomes much smoother because the etching rate at the valley cusp is much lower than elsewhere.

Figure 9 [Figure 9: see original paper] compares experimental and simulated morphological evolution of a pit array. Each pit evolves similarly to the single pit in Figure 8. Experimentally, pit boundaries expand and approach neighboring boundaries. The right side of Figure 9 shows the corresponding FDTD simulation, which agrees excellently with experimental results, demonstrating the effectiveness and reliability of FDTD simulation. Moreover, wet chemical etching shows promise for fabricating micro-concave optical lens arrays.

Figure 10 [Figure 10: see original paper] shows the evolution of hybrid pits with different sizes. Larger pits have 2.0 μm initial opening diameter and 3.0 μm depth, while smaller ones have 1.0 μm diameter and 1.5 μm depth, with each large pit surrounded by four small pits. For etching times under 2.5 h, pits evolve independently. After 2.5 h, boundaries approach and mingle, creating a beautiful four-leaf clover pattern. This result suggests that wet chemical etching can be used for micro-scale design and processing.

In practice, surface pits have uncertain sizes and random distributions. Figure 11 [Figure 11: see original paper] simulates evolution of randomly dispersed pits. The right subfigures show top views corresponding to left perspectives. The initial “ $t=0$ h” morphology comes from experimental AFM measurements, with initial peak-to-valley (PV) roughness of ~ 0.27 μm . FDTD simulations predict that after 2.0 h of etching, pits enlarge while PV roughness decreases to < 0.25 μm , with boundaries expanding toward each other. After 5.5 h, neighboring boundaries mingle and co-evolve, reducing PV roughness to 0.24 μm —an 11.1% decrease from the initial value. The pits become passivated and the entire surface smoothed. This passivation and smoothing effect improves surface quality and promises enhanced laser damage resistance.

4.3 HF-Based Etching Effect on Surface Cracks

Microscopic cracks are inevitable during fused silica optics manufacturing, appearing as ultra-fine line defects often invisible to the naked eye. Conventional detection methods struggle to identify these cracks, but HF-based etching exposes them.

Figure 12 [Figure 12: see original paper] shows simulated morphological evolution of a single micron-sized crack during HF-based etching. The initial 3D profile (top-left) has ~ 3 μm depth. After 0.5 h, the crack opening increases considerably while depth changes little. During subsequent etching, the crack continues widening with minimal depth change. Figure 13 [Figure 13: see original paper] shows six parallel cracks evolving similarly, with each crack opening during etching and co-evolving with neighbors. Crack depth decreases from initial ~ 1.7 μm to < 0.5 μm after 5.5 h—a reduction exceeding 70.6%, substantially improving surface PV roughness.

Figure 14 [Figure 14: see original paper] shows crossed cracks evolving during etching. The initial surface resembles a chessboard from the top view. Each crack widens during etching, and after 5.5 h, the initial square-column-like surface transforms into a bar-array-like surface with gap widths comparable to bar widths. PV roughness decreases considerably after 2.5 h, while changing little during the first 2.5 h.

To track practical crack evolution, AFM measurements were performed between successive etching phases. Figure 15 [Figure 15: see original paper] shows experimental (left) and simulated (right) evolution of a surface crack. The initial crack has a snaggle-tooth profile. After 0.5 h of etching, the teeth are “rubbed” down, transforming the jammed crack into an unobstructed furrow. Continued etching widens the crack and smooths its internal surface, with width increasing from $\sim 1.5 \mu\text{m}$ to $\sim 5.5 \mu\text{m}$ after 1.5 h. Based on the initial AFM measurement, we built a 3D model (top-right) and performed FDTD simulation (lower two views). The simulation shows the snaggle-tooth profile being “rubbed” down after 0.5 h, agreeing excellently with experiment. The “rubbed” crack continues opening and smoothing during subsequent etching. This comparison demonstrates that FDTD simulation reliably and efficiently reveals detailed mechanisms of morphological evolution during HF-based wet chemical etching.

4.4 HF-Based Etching Effect on Surface Scratches

Surface scratches represent another typical defect. As shown in the top-left of Figure 16 [Figure 16: see original paper], a scratch typically appears as an assembly of discontinuous directional cracks generated orthogonal to the scratching direction. The left series in Figure 16 shows experimental optical microscopy tracking scratch evolution. The top-right subfigure presents an analytically built 3D scratch model, with middle-right and bottom-right subfigures showing FDTD predictions. The middle series provides top views corresponding to right perspectives. Optical microscopy reveals that initial discrete cracks expand during the first 1.5 h, with borders approaching neighbors. FDTD simulation demonstrates this expansion and mingling effect (top-middle subfigures). Subsequent etching makes the scratch continuous and smooths its surface.

Figure 17 [Figure 17: see original paper] examines a wide scratch ($\sim 25 \mu\text{m}$ width) with complex morphology. Optical microscopy and AFM characterize the morphology, with results shown in top and middle series, respectively. The wide scratch contains many pits and cracks that expand after 1.5 h of etching, with internal surfaces smoothing. Continued etching causes surfaces to merge into larger concave smooth surfaces. AFM results confirm this smoothing effect. Based on initial AFM data, we built a 3D scratch profile model and performed FDTD simulation (bottom-left shows initial morphology). The simulation shows initial pits and cracks becoming larger and smoother after etching, qualitatively agreeing well with experimental results. Again, the smoothing effect improves surface quality and promises enhanced laser damage resistance.

4.5 HF-Based Etching Effect on Surface Laser Damage Sites

During routine operation of large high-power laser facilities, laser-induced damage sites inevitably form on fused silica optics surfaces. These sites grow exponentially with subsequent high-intensity laser irradiation, making it imperative to suppress their growth through one-step processing. Fortunately, HF-based etching can process all laser damage sites on an optic surface in a single submergence step. Figure 18 [Figure 18: see original paper] shows laser damage site evolution during HF-based etching, resembling the pit evolution in Figure 7. The damage site surface becomes smoothed after etching.

Hrubesh et al. from Lawrence Livermore National Laboratory demonstrated that HF-based etching significantly suppresses micron-sized laser-induced surface damage growth in fused silica.

To assess damage growth resistance of millimeter- or sub-millimeter-sized sites, we performed flat-top-shaped 351 nm, 5.0 ns, 8.0 J/cm² “1-on-1” (one shot per position) laser irradiation tests. Figure 19 [Figure 19: see original paper] compares damage growth of a typical etched site (Site 2) with an unetched site (Site 1) after single-pulse irradiation. The etched site shows minimal growth, while the unetched site grows substantially, demonstrating that HF-based etching suppresses damage growth in sub-millimeter-sized sites. Further, we monitored 48 laser damage sites on each of two 50.0 mm diameter, 5.0 mm thick optics—one etched (1#) and one unetched (2#). Figure 20 [Figure 20: see original paper] shows the statistical count of growing damage sites. On the etched 1# optic, 12 sites showed visible growth after irradiation, compared to 23 on the unetched 2# optic. Despite morphological variations among monitored sites, their comparable dimensions support the conclusion that HF-based etching suppresses damage growth in millimeter-sized sites.

Although the suppressing effect is evident, the number of growing etched sites exceeds expectations. Figure 21 [Figure 21: see original paper] shows damage growth in an etched site after irradiation. The two relatively large (heavily damaged) sites on the left exhibit apparent growth, with numerous separate damage pits appearing around their initial borders and surfaces. This growth pattern differs from unetched sites (Figure 19, top), where growth primarily involves border expansion. Meanwhile, smaller etched sites show no growth after irradiation. Thus, for etched sites of different sizes, larger sites are more prone to damage growth—indicating a size effect.

To explore this size effect, we experimentally tracked 3D morphological evolution of a millimeter-sized damage site during HF-based etching. As shown in Figure 22 [Figure 22: see original paper], the initial surface topography is very rough with high spatial frequency features. During etching, the surface smoothes into low spatial frequency features while the damage site becomes progressively deeper, with new cracks appearing around the site. Guss et al. used optical coherence tomography to reveal that damage sites contain many micro-fractures beneath the surface. Our results show HF-based etching effects on such micro-

fractures. For optics with surface laser damage, HF-based etching is anisotropic at damage sites, likely due to undetectable or weakly detectable micro-cracks beneath the site and/or changes in material physical/mechanical properties during damage formation. If these micro-cracks and property-varied material remain unmitigated, laser-induced damage growth occurs easily during high-intensity irradiation. For heavily damaged or large sites, mitigating numerous micro-cracks or property-varied material via HF-based etching is time-consuming. This may explain the finding in Ref. [26] that “Deeply etched sites show reduced, but non-zero, fluorescence emission.”

In comparison, Figure 23 [Figure 23: see original paper] shows evolution of a smaller sub-millimeter-sized damage site. The same trend appears: initial rough surface smoothes after etching, and site depth increases significantly. However, no cracks remain after 12.0 h of etching, indicating that initial micro-cracks have been removed. Combined with Figures 21 and 19, this suggests that enhanced laser damage resistance in etched sites results from micro-crack removal.

Currently, accurately modeling a laser damage site is very difficult. For simplified analysis, Figure 24 [Figure 24: see original paper] sketches damage site formation. The central sun-like region represents the laser-induced plasma explosion core near the laser exit surface. The bold black line denotes the damage site surface profile. The upper section near the flat exit surface appears as a mechanically stripped bulk material trace, while the lower section typically shows a molten surface with jet traces. Below the damage site surface, many micro-cracks (thin black lines) extend in diverging directions, forming a cracked field (brown lines). This cracked field is believed to be an intense field of laser damage precursors that likely causes damage growth if insufficiently etched. Both the cracked field and upper stripped profile are thought to result from laser-induced shock wave effects. Below the cracked field lies a deformed field (light blue line) with little micro-cracking but altered bulk material properties from laser irradiation and plasma explosion. HF-based etching rates are enhanced in both fields, causing the damage site to deepen during etching.

5. SUMMARY

This work investigated HF-based etching effects on fused silica surface fractures (pits, cracks, scratches, and laser damage sites). We experimentally characterized morphological evolution during etching using optical microscopy and 3D profilometry, modeled 3D fracture profiles, and performed FDTD simulations to predict evolution. The main findings are:

- (1) **Surface pits** become passivated and smoothed after HF-based wet chemical etching. This passivation/smoothing effect improves local surface quality and promises enhanced laser damage resistance. Wet chemical etching also shows potential for fabricating micro-optical lens arrays.
- (2) **Surface cracks** open and smooth after HF-based etching. Neighboring opened cracks co-evolve during etching, substantially improving local sur-

face PV roughness.

- (3) **Surface scratches** evolve from discontinuous to continuous, with smoothed local surfaces after HF-based etching. Internal pits and cracks in wide scratches merge with neighbors during etching, generating larger concave smooth surfaces.
- (4) **Surface laser damage sites** show improved local topography through removal of high spatial frequency fractures, with greatly suppressed damage growth via mitigation of surface and subsurface fractures. This establishes HF-based etching as a promising wet chemical repair method. However, damage site depth increases during etching, likely due to micro-cracks beneath the site and laser-induced changes in material physical/mechanical properties.

Additionally, this work proposes an explicit local-curvature-dependent etching model. FDTD simulations based on this model agree excellently with experimental results, demonstrating that FDTD simulation reliably and efficiently reveals detailed mechanisms of surface fracture evolution. Furthermore, wet chemical etching shows potential for micro-scale design and processing.

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