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Characterization of manufacturing-induced surface scratches and their effect on laser damage resistance performance of diamond fly-cut KDP crystal

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ABSTRACT

Manufacturing-induced defects have drawn more and more attentions to improve the laser damage resistance performance of KDP crystal applied in high-power laser systems. Here, the morphology of surface scratches on diamond fly-cut KDP crystal is characterized and their effect on the laser damage resistance is theoretically and experimentally investigated. The results indicate that surface scratches could lower laser-induced damage threshold (LIDT) by modulating incident lasers and producing resultant local light intensifications. The induced maximum light intensity enhancement factors (LIEFs) are dependent on scratch shapes and dimensions. The diffraction effects originating from scratch edges are responsible for the strongest light intensification. Even for ultra-precision finished KDP surface with scratches that well satisfy the currently applied scratch/dig specification, the induced LIEFs are quite high, indicating that the actual defect dimension allowance should be amended and specified according to the defect-induced LIEFs. The effect of scratches on laser damage resistance is experimentally verified by the tested LIDT, which is approximately consistent with the simulation one. The morphologies of laser damage sites further confirm the role of scratches in lowering LIDT. This work could offer new perspective and guidance for fully evaluating the performance of ultra-precision manufactured optical materials applied in high-power laser facilities.

Introduction

Serving as frequency converter and optoelectronic switch, potassium dihydrogen phosphate (KH_2PO_4, KDP for short) crystal has been widely applied in laser-driven Inertial Confinement Fusion (ICF) facilities due to its unique physical and optical performances, such as large IR and UV transmittance, high nonlinear optical coefficient, excellent optical homogeneity and frequency-doubling properties [1–3]. When exposed to high-power laser circumstance, KDP crystals are susceptible to suffer from laser induced damage, and the laser damage resistance of KDP component has seriously limited the output energy promotion of ICF laser facilities [4]. The laser induced damage in KDP crystal components could be classified into surface damage and bulk damage according to the locations of damage events. It is generally accepted that bulk laser damage results from local temperature increase and plasma formation induced by internal absorbing impurity defects, which are introduced in the rapid growth process of KDP crystal boule [1,5,6]. The bulk laser damage in KDP crystal commonly appears as numerous micrometer-scale pinpoints, which would remain stable in size and shape as the increase of laser shot numbers [7,8]. After years of efforts made in developing advanced crystal growth and fabrication techniques, the bulk laser damage resistance has been greatly improved that the bulk damage threshold of KDP crystal is currently comparable with that of the surface damage [9–11]. As for the surface damage, it is closely related to the superficial structural flaws and the imbedded absorbing particles, which are generated on the finished KDP surface during the manufacturing process [7,12]. As opposed to the case of bulk damage, the surface damage on KDP crystal grows dramatically with respect to the laser shot numbers [7,11]. It means that the surface flaws on finished KDP crystals are prone to trigger catastrophic laser damage and the surface damage would threaten the optical performance and lifetime of KDP components more severely than that of bulk damage. As a result, more attention should be paid on the surface flaws when we seek for effective measures to improve the laser damage resistance of

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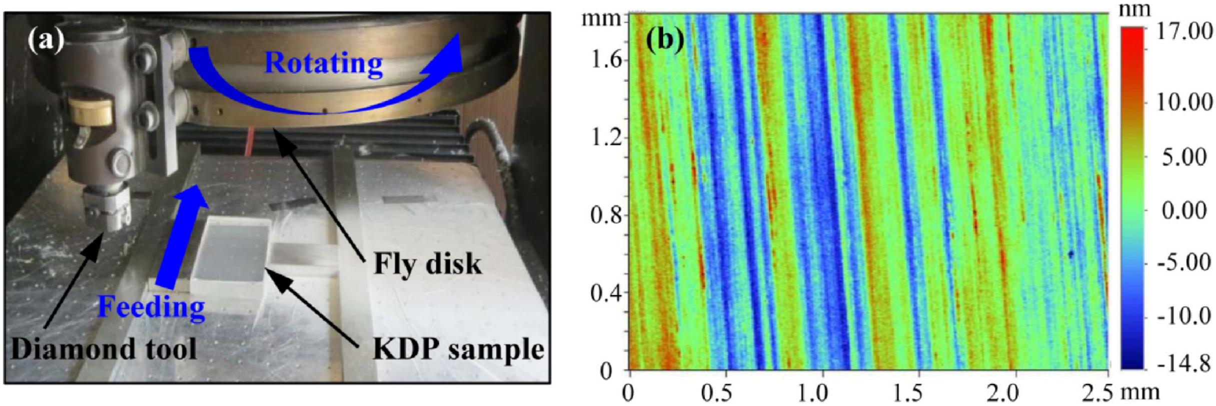

Fig. 1. (a) A homebuilt SPDT machining set-up applied to fly-cut KDP samples and (b) the typical morphology of finished KDP surface.

KDP crystal components. Plasma formation, expansion and finally explosion in laser irradiated zone are the underlying mechanisms of laser-induced damage in optical materials [4,6,12]. The laser damage on optical surface arises from local light intensity enhancements caused by manufacturing-induced surface flaws, which would incur local energy concentration and correspondingly offer sufficient energy for triggering plasma formation and explosion by photo-ionization and avalanche ionization. Hence, investigating the light intensifications caused by surface flaws is an effective way to evaluate the laser damage resistance performance of mechanically manufactured optical components.

KDP crystal has been regarded as one of the most difficult-to-cut materials due to its weak mechanical and physical properties, such as high water solubility (require non-aqueous processing), low fracture toughness (easy to fracture under slight deformation) and thermal sensitivity (prone to crack with slight temperature change) [13,14]. Various advanced ultra-precision machining methods were previously proposed to cut the KDP materials and single point diamond turning (SPDT, also termed diamond fly-cutting) has been currently deemed as the most suitable method to fabricate high-quality KDP optical surfaces with large aperture [12,13,15]. Even though the high-quality KDP surfaces required by ICF laser facilities would be basically achieved by using SPDT method, it is still a great challenge to fulfill the volume fabrication of defect-free KDP surfaces. For example, since the KDP material is soft and brittle, it is inevitable to introduce surface flaws (e.g., micro cracks, dents and scratches) on the finished surfaces in the actual machining and handling processes of KDP components [12,16,17]. The laser-induced damage threshold (LIDT) of practically machined KDP component is far lower than that of the intrinsic one and the machining-induced surface flaws are believed to be responsible to this fact [12,18,19]. Based on this, researchers from the ICF laser facilities have drawn particular attentions to the flaws on their actually manufactured optical surfaces. The world's largest ICF laser facility, National Ignition Facility (NIF) constructed in the U.S., has strictly restricted the scratch width and dig diameter on the finished KDP surfaces to be smaller than 40 μm and 150 μm, respectively [13]. Recently, researchers from China carried out laser damage test on large-aperture KDP crystal (360 mm × 360 mm) based on their large ICF laser facility. They experimentally observed that surface damage occurs prior to bulk damage. The surface scratches produced in the manufacturing process would initiate surface damage craters, the size and number of which present growth behavior with subsequent laser shots [20]. For the sake of safe operation of large KDP crystals, they concluded that a substantial effort should be made in the future on the surface laser damage, especially those caused by surface scratches. Hence, it is of great practical and theoretical importance to systematically investigate the effect of manufacturing-induced surface scratches on the laser damage resistance of diamond fly-cut KDP crystals.

Some previous efforts have been made to explore the role of surface flaws produced during the manufacturing process in affecting the laser damage properties of optical components. In the simulation aspect, the distributions of light intensity or electric field were modeled using finite-difference time-domain (FDTD) method to describe the local energy concentration caused by surface micro-flaws [12,16,17,21]. It was found that the descending LIDTs of machined optical surfaces were closely related to the local light intensity enhancements caused by flaws. Some surface flaws with specific shapes and dimensions (e.g., conical cracks) would produce light intensity enhancement factor as high as hundreds of times, which is sufficiently high to affect the underlying laser damage mechanisms of photo-ionization and avalanche ionization processes [12,14,17]. In the experiment aspect, artificial surface flaws (e.g., indentations and scratches) were deliberately prepared on fused silica and the laser damage experiments were performed to qualitatively figure out the optical properties of surface flaws and their relation with laser damage resistance [22–24]. However, direct experimental evidence of laser damage induced by practical surface scratches has been rarely reported previously for KDP optics. Besides, even though the maximum width allowance of surface scratch was empirically specified for practically machined KDP crystals, the underlying mechanisms on how the surface scratches affect the laser damage resistance of KDP components are still not well understood [13]. Furthermore, surface scratches on practically machined KDP crystals have been seldomly reported and their contribution to the low laser damage threshold of actual KDP optics has been not fully considered. In this work, surface scratches on diamond fly-cut KDP crystals are firstly characterized by optical microscope, atomic force microscope (AFM) and optical profiler. Then, the light intensifications caused by surface scratches are simulated using FDTD method to theoretically investigate the effect of surface scratches on the laser damage resistance of KDP components. The laser damage test is finally performed on artificial and actual scratches, and the evidence of laser damage caused by surface scratches is given to validate the simulation results.

Method and model

Characterization of scratches on diamond fly-cut KDP surface

Fig. 1 shows the homebuilt SPDT machining set-up applied to fly-cut KDP samples and the typical morphology of finished KDP surface. The SPDT ultra-precision machine developed by Harbin Institute of Technology, is capable of efficiently finishing high-precision and large-size optical surfaces with nm-level surface roughness. The details of operating principle and machining process of SPDT ultra-precision machining could be found in [25]. In this work, a 100 mm × 50 mm × 10 mm KDP sample is amounted horizontally and fed linearly along the movement platform. The combined movements of diamond tool and KDP sample produce ultra-smooth flat KDP surface.

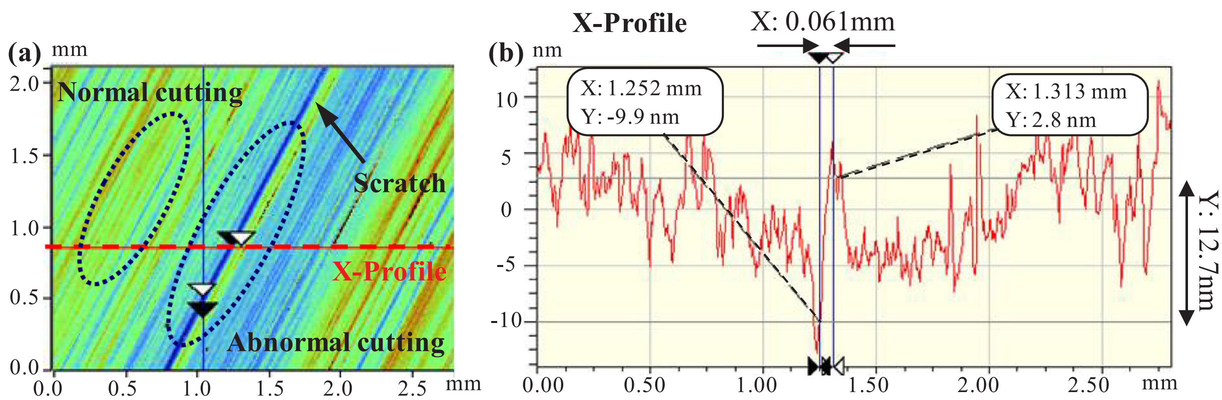

Fig. 2. (a) The morphology and (b) section profile of surface scratches measured by optical profilometer on typical diamond fly-cut KDP surface.

Fig. 1(b) shows the morphology of a typical SPDT finished KDP surface measured by optical profiler. As can be seen, obvious scratches are generated on the finished surface even though the surface roughness Ra is 3.87 nm. The surface scratches with various depths and widths are different from the SPDT inherently generated periodic micro-waveness, which are caused by the discontinuous cuttings of diamond tool [26–28]. The amplitude and period of micro-waveness are uniform, and they are equal to the feed speed and scallop height, respectively. The scratches on the finished surface are nonperiodic and the amplitudes or depths vary from each other.

Figs. 2 and 3 present detailed morphological and geometric information of the surface scratches measured with optical profilometer (NewView 8200 by Zygo), optical microscope (VHX-5000 by Keyence) and atomic force microscope (AFM, Dimension Icon by Bruker). The VHX-500 optical microscope with magnification from 500X to 5000X is used to locate the positions of surface scratches. The combined application of NewView 8200 optical profilometer (mm-level scan range, sub-micron level lateral resolution and 0.1 nm vertical resolution) and Dimension Icon AFM (typical 90 μm × 90 μm scan range, ≤ 0.15 nm lateral position accuracy and vertical resolution of tens of picometers) enables the precision measurement of the width and depth information of surface micro scratches. As shown in Fig. 2(a), two distinct regions coexist on the SPDT finished KDP surface, which are smooth surface finished by ideal normal diamond cutting and flawed surface finished by abnormal cutting. The smooth normal cutting region is textured with SPDT inherently generated periodic micro-waveness. The amplitude of surface micro-waveness on this region is several nanometers, which possesses the same order of magnitude to that of the surface roughness

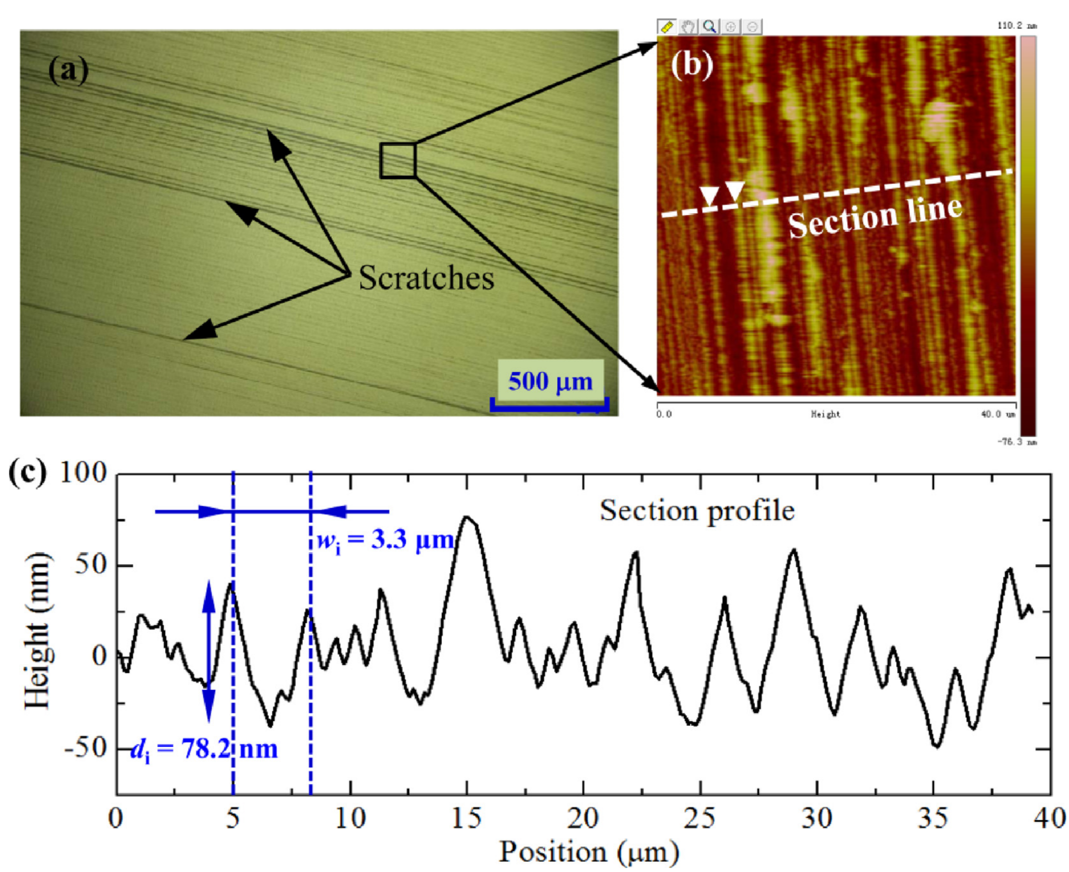

Fig. 3. The morphology of surface scratches measured by optical microscope (a) and atomic force microscope (b) and section profile of surface scratches measured by atomic force microscope (c) on typical diamond fly-cut KDP surface.

(3.87 nm). As for the flawed surface region, evident isolated scratch with 61 μm width and 12.7 nm depth is generated and the scratch depth is far larger than the surface roughness. The abnormal cutting process incur generation of flawed surface with scratches, which may arise from the formation and detachment of built-up edge involved in the diamond fly-cutting process [29].

The morphology of surface scratches in Figs. 2 and 3 indicate that the scratches distribute randomly on diamond fly-cut KDP surface and the scratch morphology is so complicated and irregular that it is very difficult to build the same scratch models as the real ones for investigating the effect of scratch structural parameters on the laser damage resistance. Actually, the section profile of real surface scratch in Fig. 3(c) appears that the profiles of surface scratches caused by abnormal cutting could be classified into two types of basic profiles: (a) circular profiles with blunted tips and (b) triangular profiles with sharp tips. In light of this, the real scratch profiles are simplified into circular and triangular scratches in the simulations for quantitatively investigating the effect of scratch structural parameters on the laser damage resistance. Furthermore, a large amount of statistic results demonstrate that the scratch width ranges from several microns to tens of microns and the scratch depth is in the range of sub-micron to several microns. In the following section, the FDTD models and structural parameters of surface scratches are established according to the experimentally measured morphological information of real surface scratches to investigate their effect on the laser damage resistance. Hence, the results would be credible and capable of offering theoretical guidance to fully evaluate the surface quality of practically ultra-precision processed KDP optics.

Theory and FDTD modeling

The manufacturing-induced surface defects, especially those with dimensions close to the incident wavelength ($\lambda = 1.064\,\mu m$), would greatly modulate incident lasers, resulting in serious local light intensification inside optical materials. The local light intensification would incur nonlinear increase of energy absorption to incident laser, local energy deposition and concentration, which should be responsible to the low practical laser-induced laser damage threshold of optical components [12,16,17,19]. In light of this, the light intensity distribution caused by surface scratches is numerically calculated by solving the Maxwell's equations using FDTD algorithm. The light intensity enhancement factor (LIEF) caused by surface scratch is introduced to quantitatively indicate the effect of surface scratch on the laser damage resistance, which is defined as the relative light intensity referenced to the uniform light intensity caused by ideal KDP surface without any defect [12,17].

Fig. 4 presents the schematic of proposed FDTD models for circular and triangular scratches on KDP surfaces. As can be seen, the surface scratches are set on the front surface of KDP crystal and the incident laser normally irradiates on this surface. As shown in Figs. 2 and 3, the length of surface scratch is generally far larger than the width and depth, hence a two dimensional (2D) FDTD simulation is sufficient to calculate the whole light intensity distribution inside KDP crystal [30]. In the FDTD models, the incident laser is set at $z = -2.5\,\mu m$, and the interface between KDP and air is located at $z = 0\,\mu m$. The incident laser with fundamental frequency ($\lambda = 1.064\,\mu m$) is adopted and the dimension of the whole simulation domain is $40\,\mu m \times 40\,\mu m$. The simulation domain is uniformly gridded with mesh size of $\delta = 50\,nm$, which must be smaller than $\lambda/12$ to weaken the effect of numerical dispersion caused by the FDTD algorithm and guarantee the calculation accuracy. Besides, to eliminate the effect of light reflection and scattering at the truncation boundaries on the calculated light intensity distribution in the simulation domain, Periodic Boundary Condition (PBC) and Perfect Matched Layer (PML) are applied respectively at the horizontal ($x = \pm 20\,\mu m$) and vertical ($y = 0\,\mu m$ and $y = 20\,\mu m$) boundaries [30,31]. More details on the FDTD simulation and KDP optical parameters can be found in [12]. It should be noted that a fictitious scratch is set symmetric to the PBC boundary in the implementation of PBC boundary condition. In order to get rid of the effect of neighboring fictitious scratch, the vertical dimension of the simulation domain is set to be much larger than the sizes of the surface scratches. In this work, the circular and triangular scratches with various structural parameters (diameter D for circular scratch, and scratch width w_t and depth d_t for triangular scratch) are considered to systematically investigate the effect of scratch shape and size on the laser damage resistance of KDP crystal components.

Laser damage test on diamond fly-cut surface with scratches

In order to verify the FDTD simulation results and experimentally investigate the effect of surface scratch on the laser damage resistance of KDP crystal, laser damage test is performed on surface scratches. In the laser damage test, a Nd: YAG SAGA laser with 1064 nm wavelength, 6.4 ns pulse width and 10 Hz repetition rate is applied to tightly focused on the scratch area of SPDT fly-cut KDP surface. The detailed laser parameters applied in the laser damage test is presented in Table 1. The laser induced damage thresholds (LIDTs) on various scratch areas are tested following the R-on-1 protocol [12,32]. In the R-on-1 test protocol, the scratch area is irradiated by incident laser with laser fluence ramping up until the damage is triggered. The LIDT is determined as the lowest laser fluence when the damage takes place. In the R-on-1 test protocol, a total of 10 identical surface scratches are required to be tested and the eventual LIDT is defined as the average value of the lowest laser fluences obtained in the test of these scratches.

In this work, the laser damage test is performed on the real surface scratches as shown in Figs. 2(a) and 3(a) to verity the role of surface scratch in lowering the laser damage resistance of KDP crystal. But, when we attempt to measure the LIDT of each type of surface scratch, a total of 10 identical surface scratches with the same morphology and size are required. From the measured morphology of surface scratches shown in Figs. 2 and 3, it is concluded that the scratches are generated randomly on the SPDT finished surface, and it is impossible to find identical scratch on the real finished KDP surface. To solve this problem, by using scratcher, indenter and machining tool, artificial surface defects (e.g., fracture indentation, micro-pit and scratch) with the same properties and size to the real manufacturing-induced surface defects are always prepared for the laser damage experiments to experimentally explore their effect on LIDT [22–24,33]. Here, micro-milling cutter with ball-end nose is employed to prepare artificial surface scratches on KDP surface for the laser damage experiment to determine the LIDTs of various scratches. Fig. 5 shows the schematic of artificial scratch preparation process and the applied micro-milling cutter.

As can be seen in Fig. 5, the radius of applied micro-milling cutter is 50 μm and the tilted high-speed rotating micro-milling cutter combined with linear feeding movement of KDP sample can produce surface scratches with controllable dimensions. Since the KDP crystal is a kind of soft and brittle material, both plastic and brittle scratches with various dimensions could be produced by adjusting the micro-milling parameters of tool tilting angle (θ_s), cutting depth (a_p), tool rotating speed (n_t) [34,35]. In this work, three types of scratches: plastic mode, plastic-brittle mixed mode and brittle model are generated on the KDP surface. The applied micro-milling parameters for these three types of surface scratches are listed in Table 2. As can be seen, with tool radius of 50 μm and cutting depth of 3 μm, the scratches with depth of 3 μm and width of 40 μm are expected to be produced. According to the brittle-ductile transition condition of KDP crystal, purely ductile scratch (named as No. 1) could be achieved by applying tool tilting angle of + 30°, cutting depth of 3 μm and tool rotating speed of 50 000 RPM [35]. By reducing the tool rotating speed to 5 000 RPM, brittle fracture could be introduced in the plastic scratch and surface scratch with plastic-brittle mixed mode is then produced (named as No. 2). To produce purely brittle scratch (named as No. 3), the tool tilting angle is

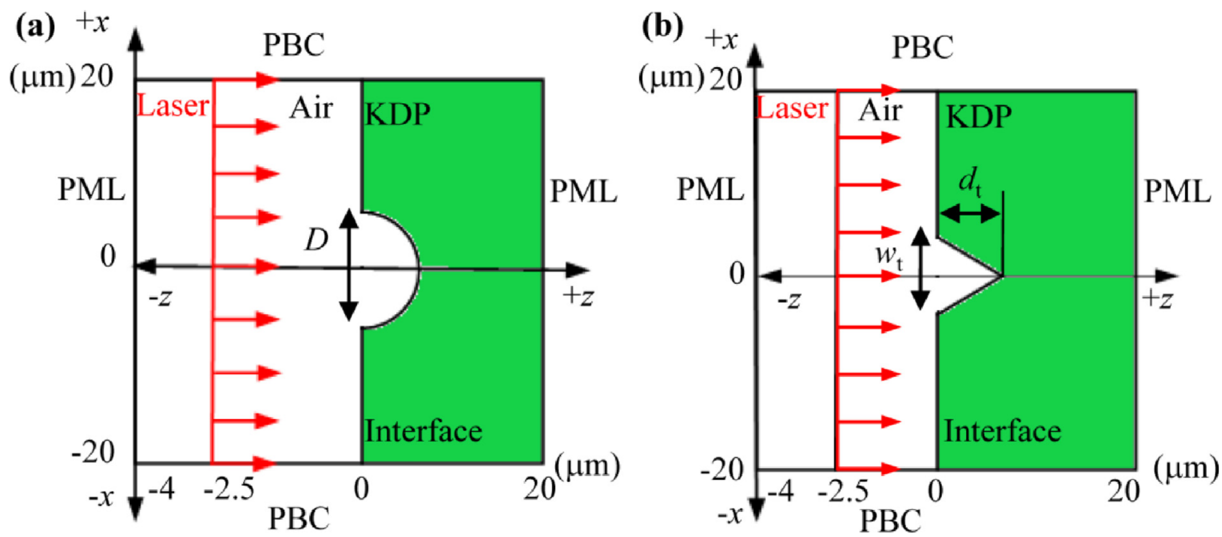

Fig. 4. Schematic of the FDTD models for circular (a) and triangle (b) scratches on KDP surface used for the following simulations.

Table 1
The applied laser parameters for laser damage test on KDP surface scratches.

Pulse widthτ_p/ns	Wavelength λ/nm	Repetition rate ν/Hz	Beam diameter D_b/μm	Incident angle θ_i/deg
6.4	1064	10	454.3	0

adjusted to − 30° (negative milling) and the KDP material is removed in totally brittle mode [34].

Fig. 6 presents the morphology of prepared three types of surface scratches. One can see that all of the three types of scratches share the same dimensions. The width and depth of the scratch are roughly 40 μm and 3 μm, respectively, which is included in the dimension range of the real scratches on the practical SPDT fly-cut KDP surface. Hence, these artificial surface scratches could be used to carry out the LIDT test experiments. In addition, as expected, the No. 1 scratch in Fig. 6(a) presents purely plastic appearance, while for the No. 3 scratch in Fig. 6(c), the brittle fracture features totally exists in the edge and interior regions of the scratch. As for the No. 2 scratch in Fig. 6(b), besides of plastic scratch region like No. 1 scratch, some slight brittle fracture features are also generated in the lower edge region of the scratch.

Results and discussions

Light intensifications caused by scratches with various shapes

Fig. 7 presents the simulated light intensification with the presence of circular and triangular surface scratches. Generally, when the incident laser irradiates ideally flat SPDT finished KDP surface without any defect, the light intensity inside KDP crystal should be uniformly distributed. However, the simulation results in Fig. 7 indicate that the light intensity distribution is seriously distorted with the modulations of circular and triangular surface scratches. It means that the manufacturing-induced surface scratches have great impact on the laser damage resistance of KDP crystal component. As seen in Fig. 7, the nonuniform light intensity distribution arises from diffraction ripples originating from the scratch edges, standing waves formed by the interference between incident and reflective waves, and slight pure reflective light intensity. The standing waves appear as a serious of parallel hotspots mainly located in the region of $-2.5\,\mu m \le z \le 0\,\mu m$, and the pure reflective light intensity appears as weak reflective light waves in blue color that located in the region of $-4\,\mu m \le z \le -2.5\,\mu m$, which are both in the air. Since the laser damage is related to the light intensification in the bulk of optical material, only the nonuniform light intensity distribution inside KDP crystal is taken into consideration. For the case of circular scratch shown in Fig. 7(a), the maximum LIEF inside KDP crystal is caused by the diffraction ripples from the scratch edges, which is 1.37 and located on the rear surface of KDP. It means that with the presence of circular scratch, the maximum light intensity on the rear surface of KDP crystal is 1.37 times as large as that of ideally flat surface without any defect.

Compared to the simulated results for circular scratch shown in Fig. 7(a), the light intensity distribution caused by triangular scratch is more complicated. Besides of the aforementioned physical effects incurring nonuniform light intensity distribution, the interference between the transmitted lights at KDP surface and triangular scratch surfaces produces a serious of enhanced light intensity ripples, which are roughly perpendicular to the scratch surfaces. Even so, the maximum LIEF is still caused by the diffraction ripples, originating from the

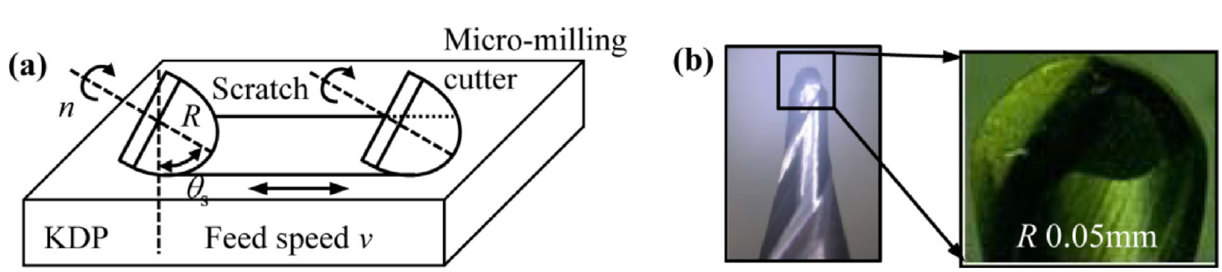

Fig. 5. Schematic of the artificial scratch preparation process (a) and the applied micro-milling cutter (b).

Table 2
The micro-milling parameters applied to prepare artificial scratches on KDP surface.

Scratch No.	Tool tilting angle θ_s (°)	Cutting depth a_p (μm)	Tool rotating speed n (RPM)	Scratch morphology
No. 1	+30	3	50 000	Plastic
No. 2	+30	3	5 000	Plastic and brittle
No. 3	−30	3	50 000	Brittle

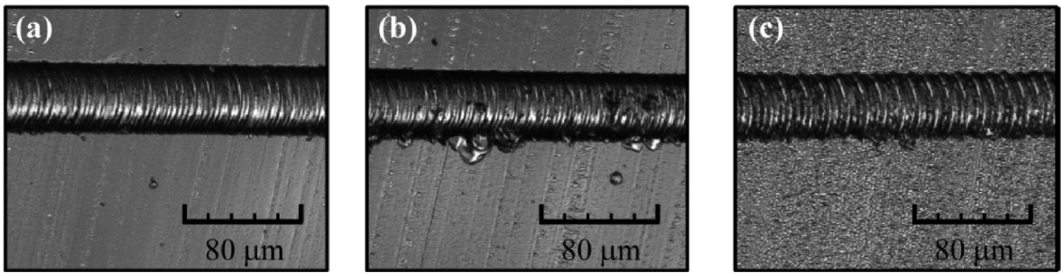

Fig. 6. Morphology of three types of artificial scratches on KDP surface: (a) Plastic scratch (No. 1); (b) Plastic and brittle mixed scratch (No. 2); (c) Brittle scratch (No. 3).

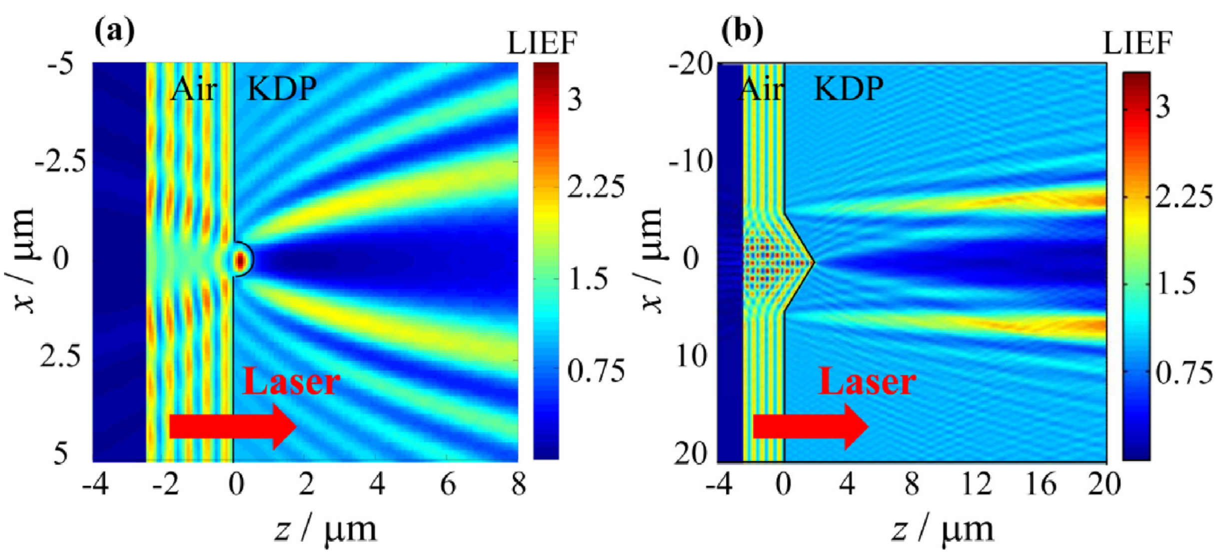

Fig. 7. Simulated light intensification distribution caused by circular (a) and triangular (b) scratches on KDP crystal surface.

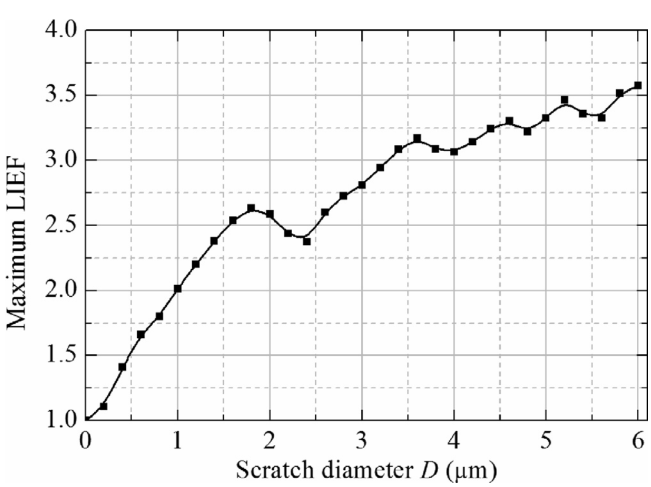

Fig. 8. Variation of maximum LIEF caused by circular scratch with respect to scratch diameter.

scratch edges. The maximum LIEF is 2.59, which is much larger than that of circular scratch shown in Fig. 7(a), but still located on the rear surface of KDP crystal. The phenomenon that the maximum LIEFs caused by both circular and triangular surface scratches are located on the rear surface indicates that the rear surface of KDP crystal is more prone to be damaged by incident lasers with the existence of manufacturing-induced front surface scratches, which is consistent with the experimental results that the laser damage on the rear surface is much more serious than that of the front surface [17,36].

Light intensifications caused by scratches with various structural parameters

The structural parameters of surface defects possess significant effect on the laser damage resistance of optical components. Exploring the variations of LIEFs with respect to the structural parameters of manufacturing-induced surface defects could offer theoretical basis and practical guidance for the manufacturing and testing engineers to normalize the defect specifications (e.g., defect size, shape, distribution and species) on finished optical surfaces.

Fig. 8 presents the variation of maximum LIEF caused by circular surface scratches with respect to the scratch diameter (D), and Fig. 9 shows the light intensity distributions caused by circular scratches with

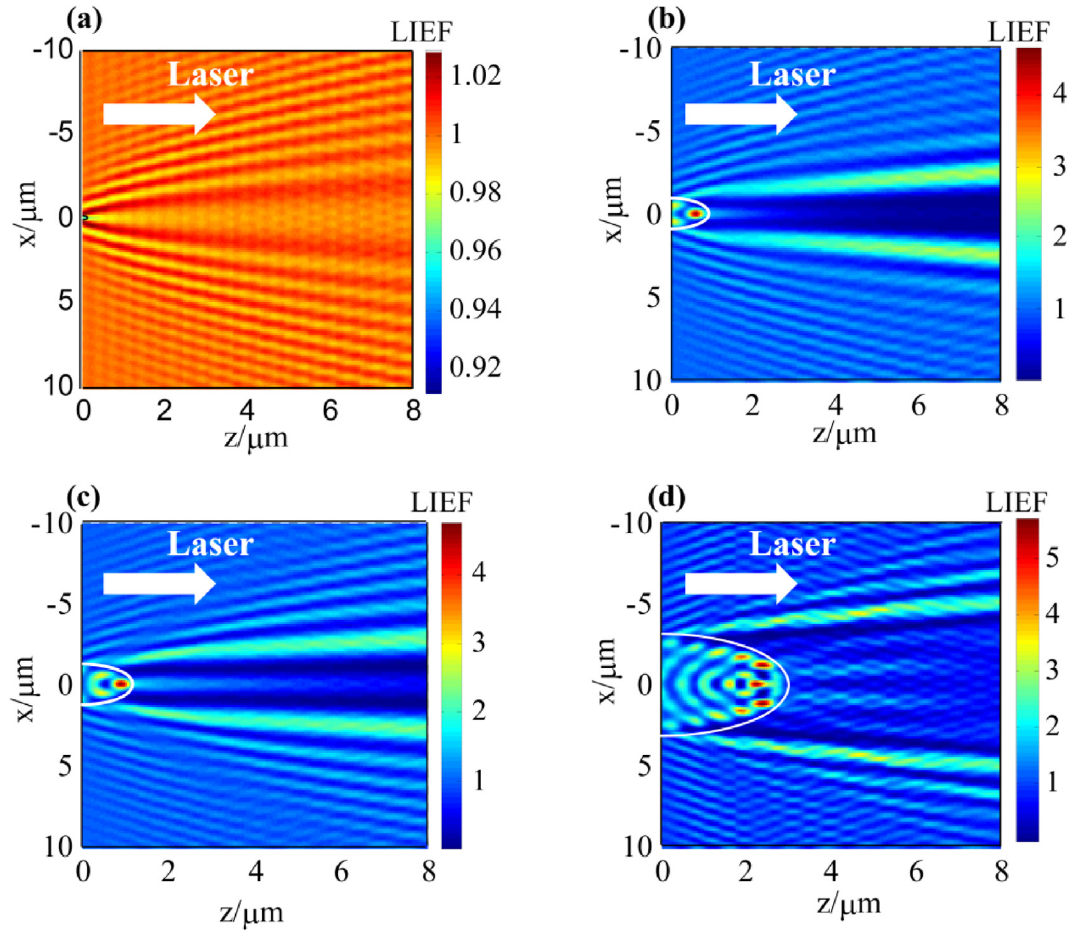

Fig. 9. Simulated light intensity distributions caused by circular scratches with various scratch diameters: (a) D = 0.1 μm; (b) D = 1.84 μm, (c) D = 2.4 μm and (d) D = 6 μm.

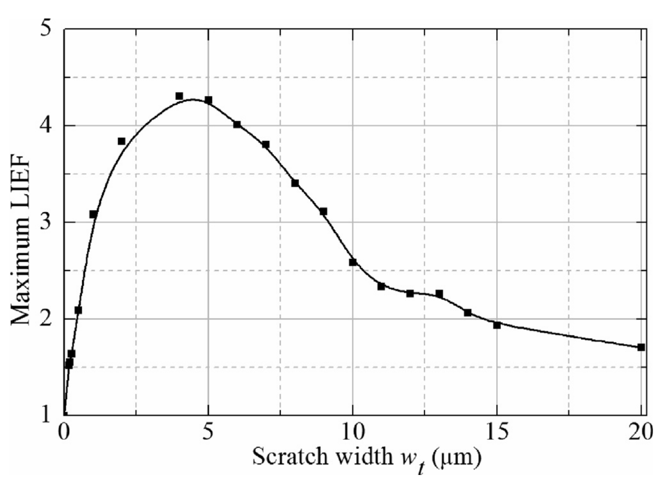

Fig. 10. Variation of maximum LIEF caused by triangular scratch with respect to scratch width w_t. The scratch depth keeps constant at d_t = 2 μm as the width w_t increases.

D = 0.1 μm, 1.84 μm, 2.4 μm and 6 μm. One can see that with the increase of scratch diameter, the maximum LIEF rises sharply for $D \le$ 1.84 μm, and then gradually increase afterward with a certain fluctuation. As shown in Fig. 9(a), when D = 0.1 μm, the surface scratch is very small, but obvious diffraction ripples cause by scratch are still generated. However, the induced maximum LIEF is very small (maximum LIEF = 1.03), which is almost equal to that caused by ideally flat KDP surface without any defect. When 0.1 μm $\le D \le$ 1.84 μm, the maximum LIEF roughly presents linear rise with increasing scratch diameter. As shown in Fig. 9(b), for scratch width D = 1.84 μm, the extreme value of maximum LIEF reaches up to 2.65. The light intensification in the two symmetrically distributed diffraction ripples is much larger than those other enhanced ripples. When $D >$ 1.84 μm, the maximum LIEF appears an overall rising tendency with the increase of scratch diameter. One can see that in Fig. 9(c) and (d) the scratch-induced diffraction effect is very strong. The maximum LIEFs caused by surface scratches with D = 2.4 μm and D = 6 μm are 2.38 and 3.57, respectively, which are large enough to incur local energy concentration and laser damage. It can be concluded that the maximum LIEF caused by circular scratches overall ascends with the increase of scratch diameter. The maximum LIEF is very large for circular scratch with $D >$ 2.4 μm, and surface scratches in this dimension range should be strictly excluded in the practical manufacturing process of KDP crystal components. This result is in contradiction with the flaw specification of large-aperture KDP crystal components, which is empirically proposed by the U.S. NIF laser facility that the scratch width allowance is 40 μm [13]. Hence, for the high-quality KDP components applied in high power laser systems, the flaw dimensions allowance should be refined and amended according to the effect of flaw parameters on the laser damage resistance.

Fig. 10 presents the variation of maximum LIEF caused by triangular surface scratches with respect to the scratch width (w_t), and Fig. 11 shows the light intensity distributions caused by triangular scratches with w_t = 1 μm, 4 μm, 15 μm and 20 μm.

One can see that as the increase of triangular scratch width, the maximum LIEF caused by surface scratch experiences a sharp increase first for $w_t <$ 4 μm, and then gradually decreases for $w_t >$ 4 μm. When

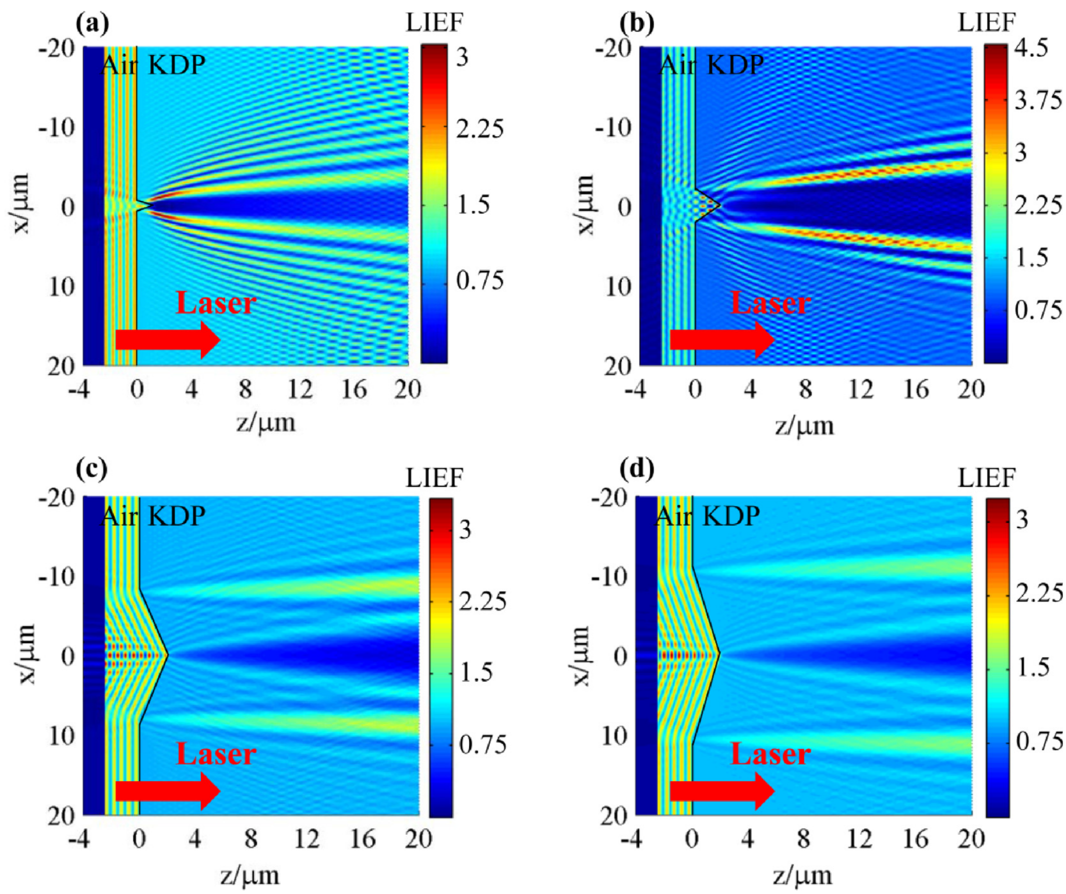

Fig. 11. Simulated light intensity distributions caused by triangular scratches with various scratch widths: (a) w_t = 1 μm; (b) w_t = 4 μm, (c) w_t = 15 μm and (d) w_t = 20 μm.

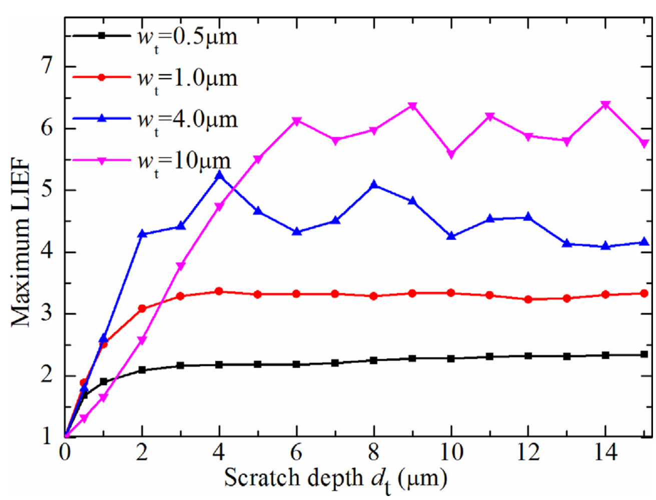

Fig. 12. Variation of maximum LIEF caused by triangular scratch with respect to scratch depth d_t. The scratch width keeps constant at w_t = 0.5 μm, 1.0 μm, 4.0 μm and 10 μm, respectively as the depth d_t increases.

the surface scratch width w_t is 4 μm, the maximum LIEF reached the peak of 4.31. For small scratch width w_t = 1 μm, the induced light intensification in Fig. 11(a) is primarily caused by the diffraction ripples, right beneath the scratch edges. As for the light intensification caused by scratch width of w_t = 4 μm shown in Fig. 11(b), besides of the diffraction ripples, the interference effect between the transmitted lights at KDP surface and triangular scratch surfaces is obvious as well. But the maximum LIEF is caused by the diffraction ripples. When the scratch width is larger than 15 μm, the induced light intensification inside KDP crystal is small that the maximum LIEF caused by triangular scratch width of w_t = 15 μm is only 1.71. This result could explain the repairing effect of KDP crystal by micro-milling that the light intensification inside KDP optics would be weakened and the laser damage resistance would be improved by removing the initial surface defects or damage sites with wide mitigation contours, such as spherical, conical and Gaussian profiles [32,37].

Fig. 12 presents the variation of maximum LIEF caused by triangular surface scratches with respect to the scratch depth (d_t) with w_t = 0.5 μm, 1 μm, 4 μm and 10 μm. One can see that as the increase of triangular scratch depth, the maximum LIEF caused by surface scratch firstly ascends dramatically, and then roughly remains stable when the depth reach a critical value. The evolution tendency of LIEF caused by triangular scratch with respect to scratch depth is similar to that caused by micro-pit defect as reported in [21]. The difference is that the critical depth for micro-pit defect is constant, while for triangular surface scratch in Fig. 12, the critical depth is variable and dependent on the scratch width. The critical depth is 2 μm for small width scratch ($w_t \le$ 4 μm), while for large width scratch ($w_t >$ 4 μm), it is roughly 5 μm. The results shown in Fig. 12 also exhibit the relations of maximum LIEFs with scratch width. As can be seen, for scratch depth of d_t = 2 μm, the maximum LIEF caused by triangular scratch with w_t = 4 μm is the highest, followed by w_t = 1 μm and w_t = 0.5 μm. While for w_t = 10 μm, the induced maximum LIEF is lower than those caused by w_t = 1 μm and w_t = 4 μm. This is well consistent with the results shown in Fig. 10 that as the increase of scratch width, the maximum LIEF caused by surface scratch experiences sharp increase firstly for $w_t <$ 4 μm, and then gradually decreases for $w_t >$ 4 μm.

Fig. 13 shows the light intensity distributions caused by triangular

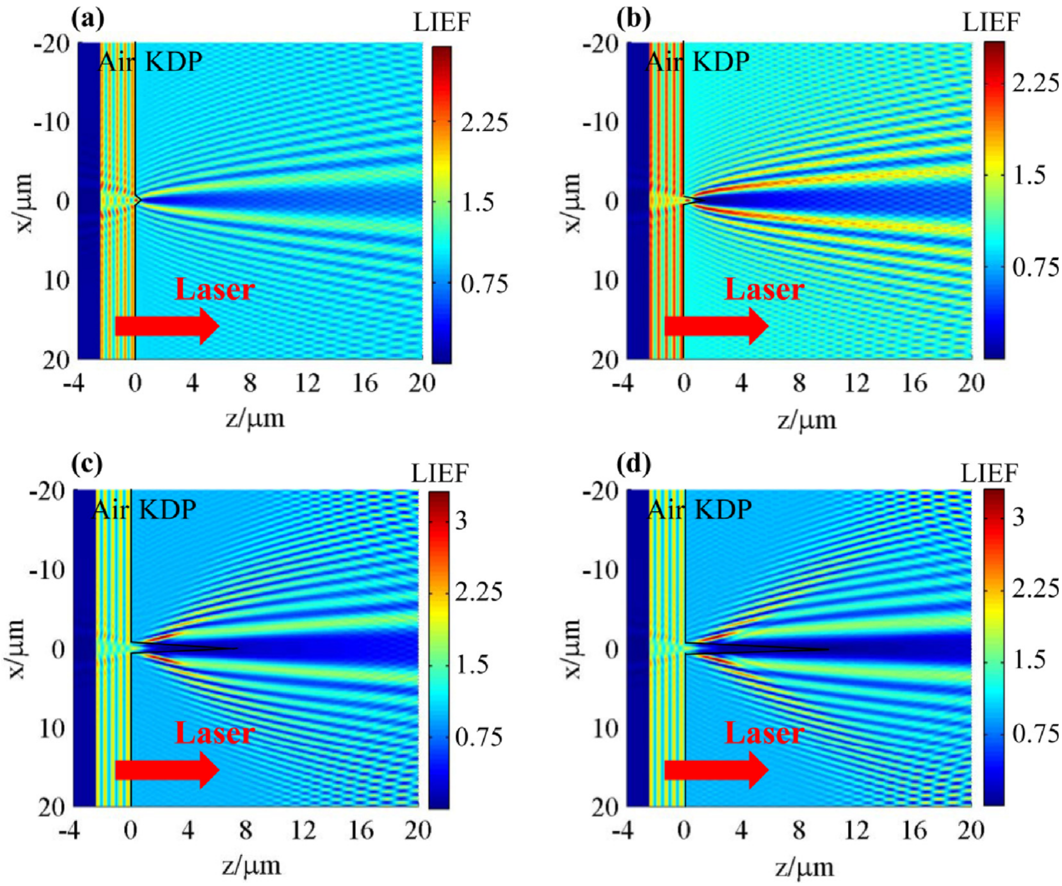

Fig. 13. Simulated light intensity distributions caused by triangular scratches with various scratch depths: (a) d_t = 0.5 μm; (b) d_t = 1 μm, (c) d_t = 4 μm and (d) d_t = 10 μm.

Table 3
Comparison of tested LIDTs of pristine and flawed KDP surface with various scratches.

Surface No.	Pristine surface	Surface with scratch		
		No. 1	No. 2	No. 3
LIDT (J/cm^2)	7.85 ± 0.24	4.25 ± 0.32	4.18 ± 0.39	3.94 ± 0.42

scratches with various depths of d_t = 0.5 μm, 1 μm, 4 μm and 10 μm. As can be seen, with the increase of scratch depth, the weakened light intensity region in blue color which is located right beneath the triangular scratch expands gradually, while the two enhanced refraction ripples which are symmetrically located beneath the scratch edges gradually become narrower. As a result, the laser intensity is more localized and concentrated inside KDP crystal with the increase of scratch depth for d_t = 0.5 μm, 1 μm and 4 μm. That is why the maximum LIEF caused by triangular scratch increases firstly with the increase of scratch depth. However, as shown in Fig. 13(c) and (d), when the scratch depth is large enough and reaches a critical value, the light intensification is localized to a certain small region and the induced LIEF keeps almost stable.

Laser-induced damage on KDP surfaces with scratches

Table 3 shows the tested LIDTs of three types of artificial surface scratches on KDP crystals. As can be seen, the LIDT of ideally SPDT finished KDP surface without any surface scratch under 1064 nm laser irradiation is 7.85 J/cm^2. However, with the presence of plastic scratch (No. 1) on KDP crystal, the LIDT decreases to 4.25 J/cm^2. Especially for

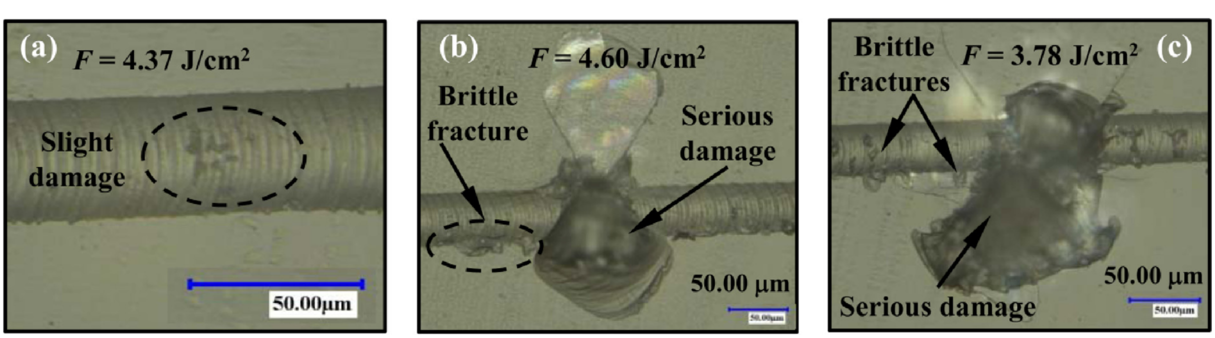

Fig. 14. Morphology of three types of artificial scratches on KDP surface: (a) Plastic scratch (No. 1); (b) Plastic and brittle mixed scratch (No. 2); (c) Brittle scratch (No. 3).

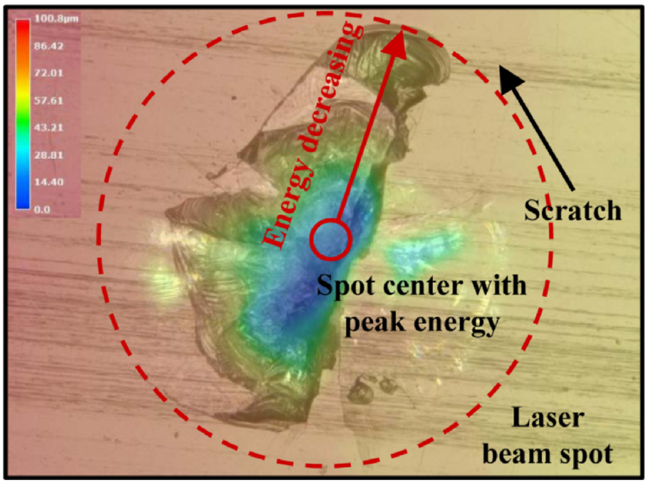

Fig. 15. Laser damage morphology caused by real-world surface scratches on practically SPDT finished KDP crystal with laser fluence of 6.57 J/cm^2.

the surface scratches with brittle fracture (Nos. 2 and 3), the induced LIDTs seriously descend to 4.18 J/cm^2 and 3.94 J/cm^2, which are just 53.2% and 50.2% of the ideally SPDT finished KDP crystal. It means that the surface scratch has great impact on the laser damage resistance of SPDT finished KDP crystal. The FDTD simulation results show that the maximum LIEF caused by surface scratch with dimensions equal to those used in the laser damage experiment is 1.51, which means that the LIDT of artificial surface scratch should be expected to be 5.20 ± 0.16 J/cm^2. The experimentally tested LIDTs for artificial Nos. 2 and 3 surface scratches are 4.18 J/cm^2 and 3.94 J/cm^2 respectively, which are roughly consistent with the numerically calculated value (5.20 ± 0.16 J/cm^2). The numerically calculated result is slightly higher than that of the experimentally tested result and the deviation between them should be due to the shape difference of surface scratches applied in the simulation and experiment. Besides, the brittle fractures introduced in the experimental scratches are another factor, making the experimentally tested LIDT on scratches lower than the numerically simulated one.

Fig. 14 presents the laser damage morphology after the irradiation of incident lasers on three types of surface scratches with laser fluences of 4.37 J/cm^2, 4.60 J/cm^2 and 3.78 J/cm^2. One can see the all the damages occur right on the scratch areas, which experimentally verifies that the surface scratch is the weak point to degrade the laser damage resistance of KDP crystal. For plastic surface scratch shown in Fig. 14(a), the laser damage is slight and takes place at the bottom of the scratch. This is because that the incident laser is focused on the scratch, and the beam spot center with peak laser energy is located right on the scratch bottom. While, for the other two types of surface scratches with brittle fracture, it experiences serious laser damage. For the case of No. 2 scratch, the brittle fracture is located on the lower cut-out edge as show in Fig. 14(b) and serious laser damage occurs right on it. For the case of No. 3 scratch, the brittle fracture is located both on the lower cut-out edge and bottom trailing scratches as show in Fig. 14(c), and the serious laser damage takes place right on these fracture regions. It can be inferred that the brittle scratch is more prone to incur serious laser damage and the surface flaws with brittle fractures must be strictly controlled in the actual manufacturing process of soft-brittle KDP crystals.

Fig. 15 exhibits the laser damage morphology caused by real-world surface scratches on practically SPDT finished KDP crystal. In the laser damage test, the incident laser with fluence of 6.57 J/cm^2 irradiates the SPDT finished KDP surface with scratches. One can see that even irradiated by laser beam with lower laser energy, the surface scratches located far from the beam spot center still incur more serious laser damage, which could offer direct evidence to verify the role of surface scratch in decreasing the laser damage resistance of KDP crystal.

Conclusion

The morphological features of manufacturing-induced surface scratches on diamond fly-cut KDP crystals are characterized using optical microscope, AFM and optical profiler. Light intensification simulations with FDTD method and laser damage experiments are performed to theoretically and experimentally investigate the effect of surface scratches on the laser damage resistance of KDP crystals. Two types of scratches with circular and triangular profiles are taken into consideration and found to have significant impact on the laser propagation behaviors. The surface scratches would severely modulate the incident laser and produce resultant local light intensifications, which are closely related to the reduction of laser damage threshold. The maximum LIEFs caused by surface scratches are dependent on scratch shapes and dimensions. Even though the light intensity distribution caused by triangular surface scratch is more complex than that caused by circular scratch, the diffraction effects originating from the scratch edges are responsible for the strongest local light intensification. The variation of maximum LIEF caused by circular scratches presents gradually ascending tendency with the increase of scratch diameter, and the maximum LIEFs are very large for circular scratches with diameter larger than 2.4 μm. As for triangular scratches, with the increase of scratch width, the induced maximum LIEFs present a sharp increase first, and then gradually decrease. While, with the increase of scratch depth, the maximum LIEFs firstly ascends dramatically, and then roughly remains stable when the depth reaches a critical value, which is variable and dependent on the scratch width. The effect of surface scratches on the laser damage resistance of KDP crystal is experimentally verified that the LIDT of surface scratch is just roughly 50% of that of ideally diamond fly-cut KDP crystal, which is approximately consistent with the light intensification simulation results. The morphologies of laser damage on artificial and real-world surface scratches both confirm the role of surface scratch in initiating laser damage. The brittle fractures distributed among surface scratches are primarily responsible for the occurrence of serious laser damage. The results in this work could provide theoretical and experimental guidance for the ultra-precision manufacturing and comprehensive evaluation of large-aperture and high-quality optical components applied in high-power laser facilities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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