Formation of periodic disruptions induced by heat accumulation of femtosecond laser pulses

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Abstract: The absorption and heat accumulation of successive ultrashort laser pulses in fused silica leads to melting of the material. We analyze the structure and formation of disruptions that occur within the trace of the molten material. We employed focused ion beam (FIB) milling to reveal the inner structure of these disruptions. The disruptions consist of several small voids which form a large cavity with a diameter of several tens of micrometer. Based on the observations, we suggest a model explaining the formation of these disruptions as a results of a fast quenching process of the molten material after the laser irradiation has stopped. In addition, we analyzed the periodic and non-periodic formation of disruptions. The processing parameters strongly influence the formation of disruptions.

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References and links
1. K. Itoh, W. Watanabe, S. Nolte, and C. B. Schaffer, "Ultrafast processes for bulk modification of transparent materials," MRS Bull., 31, 620–625 (2006).
2. R. R. Gattas, and E. Mazur, "Femtosecond laser micromachining in transparent materials," Nat. photonics, 2, 219–225 (2008).
3. A. Szameit, and S. Nolte, "Discrete optics in femtosecond-laser-written photonic structures," J. Phys. B - At. Mol. Opt., 43, 163001 (2010).
4. Y. Shimotsuma, P.G. Kazansky, J. Qiu, and K. Hirao, "Self-Organized Nanogratings in Glass Irradiated by Ultra-short Light Pulses," Phys. Rev. Lett. 91, 247405 (2003).
5. E. N. Glezer, M. Milosavljevic, L. Huang, R. J. Finlay, T.-H. Her, J. P. Callan, and E. Mazur, "Three-dimensional optical storage inside transparent materials," Opt. Lett. 21, 2023–2025 (1996).
6. N. Glezer, and E. Mazur, "Ultrafast-laser driven micro-explosions in transparent materials," Appl. Phys. Lett. 71, 882–884 (1997).
7. E. G. Gamaly, S. Juodkazis, K. Nishimura, and H. Misawa, "Laser-matter interaction in the bulk of a transparent solid: Confined microexplosion and void formation," Phys. Rev. B 73, 214101 (2006).
8. S. Juodkazis, H. Misawa, T. Hashimoto, E. G. Gamaly, and B. Luther-Davies, "Laser-induced microexplosion confined in a bulk of silica: Formation of nanovoids," Appl. Phys. Lett. 88, 201909 (2006).
9. W. Watanabe, T. Toma, K. Yamada, J. Nishii, K. Hayashi, and K. Itoh, "Optical seizing and merging of voids in silica glass with infrared femtosecond laser pulses," Opt. Lett. 25, 1669–1671 (2000).
10. H. Sun, J. Song, C. Li, J. Xu, X. Wang, Y. Cheng, Z. Xu, J. Qiu, and T. Jia, "Standing electron plasma wave mechanism of void array formation inside glass by femtosecond laser irradiation," Appl. Phys. A 88, 285–288 (2007).
purposes [5]. In addition, the voids may also align as periodic arrays along the laser irradiation aperture (NA ≈ 0.1) [7,8]. These voids can be seized and translated [9] or aligned for data storage.

Ultrashort laser pulses may induce various kinds of modifications when focused into fused silica [1, 2]. Due to nonlinear absorption processes only the focal region is modified. Beside the generation of homogeneous and even inhomogeneous refractive index changes [3, 4] the formation of small voids is possible [5, 6]. These small cavities with a volume below 1 µm³ evolve from microexplosions at very high laser intensities [7, 8]. For low pulse energies (several hundred nJ) these voids can be obtained under strong focusing conditions with a high numerical aperture (NA≈1) [7,8]. These voids can be seized and translated [9] or aligned for data storage purposes [5]. In addition, the voids may also align as periodic arrays along the laser irradiation.
[10, 11]. Even in different glasses the occurrence of small voids has been reported [12, 13].

While using low-NA objectives and low pulse energies, disruptions within the laser modified material may be formed, too. To this end, numerous pulses at high repetition rates are required to operate in the so-called heat accumulation regime [14, 15]. As soon as the temporal separation of the pulses is shorter than the thermal relaxation time of the material, heat accumulation of successive pulses occurs. Thereby, the irradiated material is heated stepwise and may be molten [15]. Due to heat diffusion the surrounding material is molten as well. The increasing temperature induces free electrons which shift the absorption point along the optical axis towards the sample surface. The resulting heat affected zone (HAZ) shows a typical teardrop-shape extended along the optical axis.

One possible application of this technique is the realization of strong bonds between transparent materials [16, 17]. However, the formation of disruptions within the traces of the molten material increases the laser-induced tensions and reduces the bond stability. In micrographs, these disruptions appear as dark spots with a size of several micrometer inside the molten material. The formation of these so-called "pearl-chains" or "micro-bubbles" appears periodically under certain irradiation conditions [18, 19], indicating a deterministic and self-induced process. While Bellouard et al. have investigated the transition between chaotic and periodic formation [18], a comprehensive explanation of the formation of these micro-bubbles is not yet known.

We report on the periodic and non-periodic formation of micro-bubbles within the traces of molten material in fused silica, using different processing parameters. At first, we describe the external and internal shape of the laser induced structures. To expose the inner structure, we use Focussed Ion Beam (FIB) milling. Based on the results obtained, we develop a theory which explains the formation of micro-bubbles as a result of laser induced aberrations. With increasing number of irradiating laser pulses, the aberrations induced by the molten material lead to a decrease of the absorption and finally to an interruption of the energy transfer to the material. Due to the rapid quenching of the glass disruptions are formed. Finally, we analyze the chaotic and periodic occurrence of disruptions with respect to the processing parameters and the proposed formation model.

2. Experimental setup

For the laser irradiation of fused silica we used a femtosecond oscillator providing pulses at a wavelength of 1030 nm, a repetition rate of 9.4 MHz, an average output power of 5 W and a pulse duration of 450 fs (Amplitude Systemes, t-Pulse 500). The repetition rate and pulse energy were varied by an external acousto-optic modulator and a halfwave plate followed by a polarizer, respectively. For the experiments, we used the second harmonic (515 nm) generated in an LBO crystal. All experiments were conducted with an aspheric lens (NA of 0.55, New Focus 5722), while using a slightly elliptic beam with a diameter (1/e^2) of 3.82 mm times 3.22 mm. We used a computer controlled position system (Aerotech ABL1000) to investigate the influence of different translation velocities. The fused silica samples (Lithosil Q1, Schott) were moved with respect to the focus to inscribe line structures. A sketch of the inscription process is shown in Fig. 1(a).

The principal challenge of a direct investigation of the inner structure of the disruptions within the traces of the molten material is to expose them for an imaging system while maintaining their integrity. Direct inscription at the surface of the sample will lead to ablation of the material. Furthermore, conventional polishing of the sample to expose buried modifications is not suited as eventual cavities will be refilled or completely destroyed by the polishing agents. In contrast, with FIB milling it is possible to reveal the underlying structure of even smaller modifications in various materials, e.g. so-called nanogratings in fused silica [20]. To reveal
the inner structure of the disruptions, we inscribed molten lines underneath the surface. After coating the surface with gold, we used a commercial FIB milling device (Zeiss Neon 60) to cut into the laser modified volume.

3. Results

3.1. Shape and inner structure of laser induced disruptions

Figures 1(b)-(d) show exemplary micrographs of laser inscribed molten lines in fused silica. We stated the applied processing parameters below the pictures. To inscribe the lines, the sample was translated along the x axis, see Fig. 1(a). The molten regions, which we retraced by dashed lines, possess a width of up to 50 µm, though the exact line width depends on the applied laser intensity [15, 21, 22]. Disruptions can be found in different sizes and quantity as dark spots within each trace of molten material. We would like to underline that we were not able to inscribe molten lines without any disruptions with the described laser system. Furthermore, disruptions were always generated at the end of a molten line, as can be seen at the end of the line in Fig.1(b), regardless of the irradiation conditions. In agreement with prior publications [18, 19] the disruptions may appear almost periodically with a distance of several tens of µm [Fig. 1(c)] or may be close together in a non-periodic manner [Fig. 1(d)]. The transition between the periodic formation and non-periodic formation of disruptions depends on the processing parameters.

| Processing Parameter       | 205 | 125 | 125 | 105 | 205 |
|----------------------------|-----|-----|-----|-----|-----|
| Pulse Energy [nJ]          |     |     |     |     |     |
| Repetition Rate [MHz]      | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 |
| Depth [µm]                 | 125 | 125 | 125 | 225 | 1275|
| Translation Velocity [mm/min] | 200 | 10  | 200 | 200 | 200 |

Fig. 1. a) Schematic of the inscription process. Ultrashort laser pulses with a repetition rate of several MHz are focused into a fused silica sample which is translated along the x direction. Within the traces of the molten material large disruptions (black spots) are formed. This appears always at the end of a molten line (b). The occurrence of disruptions within the molten material occurs either periodically (c) or non-periodically in a chaotic manner (d). The applied processing parameters are listed below the micrographs. The dashed lines retrace the molten region.
In our measurements, the periodic formation of disruptions occurred while focusing close to the surface (up to about 300 µm below the surface) and using pulse energies above 120 nJ. The distance between two periodic disruptions depends on the applied laser power and translation velocity of the sample, as can be observed in Fig.1(c). The influence of the processing parameters will be discussed in detail in chapter 6. With decreasing laser power the formation of disruptions becomes non-periodically, see Fig. 1(d). When focusing in large depths (above 500 µm below the surface), or for tighter focusing conditions, disruptions are formed non-periodically, too. In addition, the adjustment of the focusing optic plays a critical role, as misalignment leads to accumulation of disruptions. Figure 1 shows also, that a disruption affects the width of the HAZ. After a disruption is formed, the HAZ narrows and widens after several µm again. This is due to the disruption, which scatters the laser pulses and interrupts the laser heating as soon as it is formed. After the scattering object is moved out of the laser focus the absorption process and subsequent melting of the material resumes.

So far, the exact composition of these disruptions was unknown as measurements were limited to their outer boundaries. To this end, we used FIB milling to image their interior. The interior of a periodic disruption is shown in Fig. 2(b), while Fig. 2(c) originates from a non-periodically formed disruption, as indicated in Fig. 2(a). For both disruptions a repetition rate of 9.4 MHz, a pulse energy of 150 nJ and a translation velocity of 20 mm/min was used. To realize the non-periodic disruption we used an NA of 0.65 and a focusing depth of 250 µm, while we used an NA of 0.55 and a focusing depth of 100 µm for the periodic disruption.

![Fig. 2. SEM images of a FIB slice depicting the internal structure of laser induced disruptions within the traces of molten material. The details of the disruptions originate from periodic (b) and non-periodic (c) disruptions, as shown in the micrograph (a).](image)

The SEM images reveal the very complex inner structure of the disruptions. In contrast to a simple microexplosion [6–8], these modifications are partially filled with material and simultaneously consist of small cavities in various shapes. Both modifications exhibit a foam-like structure consisting of solidified material. The size of the material within the outer boundary
ranges from a few hundreds of nm up to two µm. The outer boundary of the modifications has a circular shape. The overall size of the periodically formed disruption (Fig. 2(b)) is much larger (about 11.3 µm along the y axis) than the size of a spontaneously formed disruption (Fig. 2(c) with a diameter of 7 µm along the y axis). However, as the interior and shape of the different disruptions is comparable, we assume a similar formation process.

4. Model of disruption formation

The results obtained may be used to explain the formation of disruptions. Since disruptions are always found at the end of a line we suppose that a disruption appears as a consequence of the resolidification process induced by the interruption of the laser heating. The softening point of fused silica is above 1800 K and temperature measurements of laser irradiated glass have shown, that temperatures above 3000 K can be reached easily even with single pulse irradiation [23]. On the other hand, the surrounding material exhibits room temperature. In comparison to the small heat affected zone (about \(10^{-4}\) mm\(^3\)), the volume of the cool material is quasi infinite. If the laser heating stops, the stated proportions result in a very rapid quenching process, much faster than any other glass cooling process. A fast cooling of glass leads to the freezing of glass states (at a fictive temperature) and the appropriate density [24]. Thus, different densities and resulting intensive tensions are induced within the laser irradiated volume [25]. The solidification front propagates from the outer boundary to the location with the highest temperature, which is normally the central region. It is well known, that the rapid quenching of ultrashort pulse melting of fused silica increases the number of 4- and 3-membered Si-O rings, which is accompanied by a densification of the material [26]. Hence, the material in the outer region is densified. Due to the conservation of mass the inner zone undergoes a rarefaction. In addition, the central region exhibit a large accumulation of tensions induced by the rapid quenching. Fused silica exhibits a large viscosity of about \(10^9\) Pa·s at 2000°C (e.g. borosilicate glasses have about \(10^5\) Pa·s) [27], which hinders a complete relaxation of the tensions and homogeneous reflow of material, in contrast to the mechanisms reported for borosilicate glasses [28]. As a result, the central region is not completely filled during the solidification. The inner structure of the disruptions shown in Fig.2 supports this thesis. Alternative mechanisms for the generation of disruptions as a gas-phase nucleation [29] would require a power depending treshold for the disruption formation, which we did not observe. However, the formation of the disruption is still not completely understood and requires further investigations.

Furthermore, disruptions appear also under permanent laser irradiation. In this case, we believe that aberrations of the laser focus lead to a decrease of the absorption process and induce therefore an interruption of the laser heating. A possible reason for this might be the change of the refractive index induced by the molten material. The thermo optical coefficient of fused silica is about \(1 \cdot 10^{-5}\) K\(^{-1}\). Thus, a temperature rise of 3000 K would induce a change of the refractive index \(\Delta n\) of 0.03. This change causes additional aberrations and reduces the peak intensity in the focal region. If the intensity is below the absorption threshold, the laser heating is interrupted and disruptions are formed. After the quenching the laser irradiates unprocessed material again and the absorption and the described process resumes. We have to note, that melting of the material also leads to a decrease of the absorption treshold due to the induction of defects and thermally excited electrons. Thus, the interruption of the laser heating induced by an index modification will be a competition between a decrease of the intensity distribution and the reduction of the absorption treshold.

This proposed formation process of a disruption is completely different to the well known micro-explosion of small voids [7,8]. These nano-voids were obtained under large pulse intensities, whereas the formation of disruptions occurs in the heat accumulation regime due to the interruption of the laser heating and is therefore a self induced effect.
5. Simulation of beam propagation inside fused silica

To verify our proposed model, we analyze the influence of a refractive index change on the intensity distribution in the focal region. For a start, we neglected the refractive index change induced by structure changes or shock wave generation [30] and considered only the different refractive index changes induced by a temperature rise within the modified area. The shape of the refractive index change has a Gaussian distribution along the y and z direction. Along the x direction we assumed a constant refractive index change, due to the translation of the laser focus. The size of the modifications are taken from the experimental data.

At first, we performed a simulation of the intensity distribution of ultrashort laser pulses near the focus of the optic used [31]. In the following, we used a combination of ray-tracing and wave optical propagation as suggested by Stamnes [32]. However, we restrict our simulations to the monochromatic case for the central wavelength of the laser pulses. Ray tracing is applied to calculate the propagation through the focusing optics up to a reference plane and the subsequent propagation of the optical wave into the focal region is carried out using diffraction theory. Figure 3 illustrates our simulation strategy.

![Fig. 3. Schematic of our simulation strategy. (a) The focusing optics (New Focus Asphere 5722, NA = 0.55) is modeled in ZEMAX to determine the wavefront of the incoming laserbeam at a reference sphere located in the exit pupil of the optics. (b) The optical wave is propagated from the reference sphere into the focal region using the angular spectrum operator.](image)

The focusing optics (Newport Asphere 5722, NA = 0.55) is modeled in ZEMAX (Radiant Zemax) according to the optical design data provided by the manufacture [33]. The exit pupil of the optics provides the z-position of the reference plane, that is curved corresponding to a converging spherical wave with the focus at the z-position with the smallest spot radius in the image plane. The deviations from this perfect spherical wave are exported from ZEMAX and added to the phase of the spherical wave at the reference sphere. The wave optical propagation into the focal region is implemented in MATLAB (The MathWorks, Inc.) using the angular spectrum operator [34]. The propagation of an optical wave at a source plane $U_1(x_1, y_1, z_1)$ to an observation plane $U_2(x_2, y_2, z_2)$ is calculated by

$$U_2(x_2, y_2, z_2) = \mathcal{F}^{-1} \left\{ \mathcal{F} \left\{ U_1(x_1, y_1, z_1) \right\} \cdot H(f_x, f_y) \right\},$$

(1)
with the angular spectrum operator

\[ H = \exp \left( i k_0 n z \sqrt{1 - \frac{A f_x}{n} - \frac{A f_y}{n}} \right). \] (2)

Here \( \mathcal{F} \) denotes the two-dimensional Fourier transform, \( \mathcal{F}^{-1} \) its inverse transform, \( f_x \) and \( f_y \) the spatial frequency coordinates, \( k_0 \) the wave vector in vacuum, \( n \) the refractive index, \( z \) the propagation distance, and \( \lambda \) the central wavelength of the laser pulses. The propagation of the optical wave into the material is carried out by splitting the propagation from the reference sphere to the air-glass interface and from the air-glass interface to the focal region using Eq. (1) and (2) with the respective refractive indices. To model the influence of the Gaussian shaped refractive index modification, we apply the Beam Propagation Method (BPM) [35]. The propagation of the optical wave for a discrete step \( \Delta z \) is calculated using Eq. (1) and (2) assuming a homogeneous refractive index distribution and the additional phase shift according to the laser induced refractive index modification is added using

\[ U_2(x_2, y_2, z_1 + \Delta z) = \mathcal{F}^{-1} \{ \mathcal{F} \{ U_1(x_1, y_1, z_1) \} H(\Delta z) \} \exp \{ i \Delta z k_0 \Delta n(x_1, y_1, z_1) \}. \] (3)

As refractive index modifications we consider different Gaussian distributions, which are based on experimental results. The temperature at the boundary of a modification is given by the softening point of fused silica (1600°C). For a repetition rate of 9.4 MHz and a pulse energy of 200 nJ, we measured a modification size of 92 µm (along the \( z \) axis) times 52 µm (along the \( y \) axis). At first, we assumed a central temperature of 3300°C, which means a maximal index shift of 0.03 (assuming constant thermo optical coefficient of \( 1 \cdot 10^{-5} K^{-1} \)). This temperature is still below the measured maximal temperature for single pulse heating of glass [23]. As the sample is translated in \( x \) direction, we considered a constant value along this axis. The respective refractive index modification is shown in the insets of Fig. 4. The simulations were carried out for the central wavelength of the laser pulses of 515 nm, a pulse energy of 200 nJ, a

![Fig. 4. Simulated intensity distribution inside the fused silica sample for a focusing depth of 225 µm in the (a) x-z plane and (b) y-z plane. The insets indicate the laser induced refractive index modification with a length of 93 µm and a width of 52 µm in x.](image-url)
pulse duration of 400 fs, and a beam waist of 3.5 mm at the entrance pupil of the focusing optic. Figure 4 shows the calculated intensity distribution for a focusing depth of 225 µm in the x-z plane and y-z plane. The index modification acts as a cylindric lens, due to its the translation symmetry along the x axis. A distinct focus can only be found in the y-z plane, whereas the intensity distribution in the x-z plane is broadened and depicts a width of almost 2 µm. In addition, the focus is slightly shifted towards the surface, which may easily be explained by the focusing action of the Gaussian index modification. This asymmetric focusing leads to a significant drop of the peak intensity along the optical axis.

Figure 5 shows the intensity distribution along the optical axis (x=y=0) without and with different index modifications. Without an index modification (black line) we calculated a maximal intensity of $4.5 \times 10^{13}$ W/cm² in the focal region. The existence of an index modification leads to a decrease of the maximal intensity by almost a factor of 5 (red line). For Fig. 5(a) we examined index modifications with different maximal temperature, while keeping the length of the respective molten material fixed to the experimental values. With increasing maximal temperature the achievable intensity is reduced. The red line corresponds to a large index modification induced by a temperature rise of 4000 K. This large index modification reduces the peak intensity to about 20 %. But even for a rather faint temperature rise of 2000 K (blue line) the initial intensity drops to about 35 % of the initial value.

Beside the maximal temperature, the shape of the index modification and especially the rise of the refractive index change affects the intensity distribution in the focal region. For the simulations shown in Fig. 5(b), we considered a constant temperature rise of 2000 K ($\Delta T=0.02$) and assumed different widths of the modifications. It can be seen, that a broad refractive index distribution (blue line) shows only a reduction to 75 %. Narrower index modifications (red and green line) yield a much higher reduction of the peak intensity, whereas the exact intensity distribution critically depends on the shape of the refractive index modification. For example, the narrowest refractive index modification (red line) yields a slightly higher maximal intensity than the small index modification (green line).

We have to note that the refractive index changes considered are only assumptions based on experimental results. More experimental data are required to verify the exact distribution of the index modification. Nevertheless, the principal trend is obvious. A temperature rise induces a change of the refractive index, which is asymmetric due to the translation of the sample. Such an index modification decreases the laser intensity in the focal area. Depending on the exact index modification, our simulations showed a reduction of the peak intensity to 20% of
the initial value. Due to this reduction the laser absorption may be interrupted and initiate the formation of a disruption.

For the simulation we considered only the thermally induced refractive index change. However, the melting of the glass will change the refractive index, too. In addition, we assumed a translation invariant index modification along the x-direction. However, the outer boundary of the modified area shows a rather irregular envelope, as can be seen in Fig. 6. Especially, the upper boundary of the molten material depicts a curved shape, which is attributed to the prior formation of a disruption. The curvature of the upper boundary of the molten material is increased at larger depths and lower pulse energies, as can be seen in Fig. 6(b). Thus, the actual peak intensity could be even lower, than we have calculated.

6. Periodic formation of disruptions

In the following, we investigate the periodic formation of disruptions, which occurs under low aberration conditions (which is close to the surface for most microscope objectives). To discuss the periodicity with respect to the applied processing parameters, we measured the distance between two disruptions. We considered only the periodically formed disruptions and neglected the smaller ones, which appear in the vicinity of an initial disruption. Fig. 7(a) shows an increasing distance D between two disruptions with increasing pulse energy E. In addition, the distance increases with increasing repetition rate R (for a given pulse energy) and thus generally with increasing laser power. The error (standard deviation) of the measured distances lies
between 10% and 20% and decreases slightly with increasing pulse energy, i.e. the periodicity of the disruptions increases with higher pulse energies. Although a higher translation velocity equals a lower deposited laser power per spot, we measured an increasing distance with increasing translation velocity, see Fig. 7(b). However, in Fig. 7(b) the average distance between two disruptions increases only about a factor of 5 while the translation velocity was changed from 1 mm/min to 500 mm/min.

In a next step, we calculated the number of pulses \( N \) irradiating the laser sample between two disruptions with the formula \( N = \frac{D \cdot R}{v} \). The number of laser pulses are an essential quantity as every laser pulse contributes in the stepwise heating of the material. In terms of the proposed model this means that \( N \) pulses are required to accumulate sufficient aberrations to interrupt the laser absorption and form a disruption. The number of pulses required to form a disruption with respect to the processing parameters can be seen in Fig. 7(c). With increasing pulse energy (and also higher repetition rate), the number of pulses required to form a disruption increases. In addition, a slower translation velocity leads to a larger number of pulses, too. This dependence is counterintuitive and inverse to the formation of voids induced by single laser pulses [5, 6, 8]. However, these results fit to our proposed model. For large pulse energies stronger aberrations are required to decrease the pulse intensity below the threshold than for low pulse energies. We have also seen in Fig. 5(b) that the shape of the index modification affects the reduction of the peak intensity. The index modifications induced by a high translation velocity (e.g. 500 mm/min) is much smaller than for slow translation velocities [21, 22]. Our simulations show, that a narrow index modification yields a large reduction of the intensity distribution. Consequently, less pulses are required to form a disruption at higher translation velocities. Finally we can conclude from Fig. 7(c) that the number of laser pulses required to form a disruption increases with increasing applied laser power per spot.

### 7. Non-periodic formation of disruptions

Finally, we investigate the formation of non-periodic disruptions. Here, we focus on the influence of the focusing depth. Figure 8 shows the top and side view of laser molten lines in different depths. Again, we have retraced the transition between molten and non-molten mate-

![Fig. 8. (a) Top view and (b) side view of the molten material and generated disruptions for different focusing depths. We used a red line to mark the focusing depth of 75 µm](image-url)
rial. We did not retrace the complete side views, as for deep focusing depths the lower boundary becomes very rough, as can be seen in Fig. 8(b). The width of the molten material reduces with increasing focusing depth, as can be seen in Fig. 8(a). This is due to the mismatch between the optical path within the material and the depth the lens is corrected for. For all conditions the disruptions appear primarily in the upper part of the laser modification, see Fig. 8(b). The occurrence of disruptions becomes chaotic with increasing depth. The disruptions appear almost as a continuous dark line in a certain depth (about 1 mm in Fig. 8). At a depth of 3075 µm numerous disruptions are formed, which are distributed in the entire upper third of the modification. In addition, the lower part of the molten material consists of sharp edges and needles. These needles always follow the disruptions at the upper part of the molten line.

These results may be explained by our proposed model, too. At large focusing depths, the laser focus is already distorted due to the unadapted focusing depth and the resulting aberrations. Thus, already a slight change of the refractive index may reduce the intensity below the absorption threshold and interrupt the laser heating. Consequently, disruptions appear almost along the whole line. We suppose, that no periodicity can be found due to induced defects in the glass, whose influence to the laser absorption become important for intensities close to the absorption threshold. Due to the elongation of the laser focus the shape of the molten material has a stretched cylindrical shape. The solidification front propagates toward the central axis and disruptions are formed along this axis at the region with the highest temperature, which is the upper part of the modification.

8. Conclusion

We have analyzed the occurrence and the composition of disruptions within the traces of resolidified fused silica after melting induced by ultrashort laser pulses at high repetition rates. These disruptions consist of a foam-like inner structure with cavities ranging from a few hundreds of nm up to 2 µm. Disruptions appear periodically for focusing close to the surface and high pulse energies. The largest distance between periodic disruptions is obtained while using high pulse energies and high repetition rates. The number of pulses required to form a disruption depends on the processing parameters and increases with increasing applied laser power per spot. With increasing focusing depth the appearance of disruptions becomes chaotic.

We propose, that disruptions are formed as a result of an interruption of the laser heating process. This leads to a rapid quenching of the material. For continuous irradiation this interruption may be caused by aberrations induced by the refractive index change of the molten material. These aberrations reduce the energy density until the absorption stops. Our simulations as well as the experimental results support this thesis.

The change of the refractive index increases with the induced temperature, which depends on the number of applied laser pulses. Thus, a simple change of the focusing optic would not solve this problem. Alternatively, an adaptive optic may be used to compensate continuously the self-induced aberrations.

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