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# MODELLING OF THE DIRECT LASER-INDUCED OPTICAL BREAKDOWN IN SOLID

*The problem of modeling the laser-induced optical breakdown is represented as creation universal method for all media – from gases to solid. It is the first attempt of observation this problem in main details in whole. Level of complexity of this problem is shown. From physical-chemical point of point of view the optical breakdown is the regime of fool breakage of all chemical bonds in irradiated matter in zone of laser irradiation. In this case we can determine the threshold of breakdown of irradiated matters with help methods of Relaxed Optics. This regime may be received with help three ways. First is thermal. In this case the basic relaxation of first order processes of optical excitation are thermal. Examples of these process are regimes by continuous and millisecond laser irradiation of matter. Second is plasma. In this case the main role of the optical breakdown has process of formation "collective" electromagnetic (electron-ionic) process. The examples of this process are the irradiation in the millisecond or nanosecond regimes of irradiation. In this case laser-induced plasma radiated continuum optical spectra in all direction (star effect). Third is directing optical. In this case we have direct multiphotonic ionization and these processes have oriental nature. The second order irradiation has Cherenkov nature. The experimental data were received for nanosecond, picosecond and femtosecond regimes of irradiation. This differentiation is connected with various nature of relaxation of first-order optical excitations. The comparative analysis of three types modeling is represented. We show that third direct laser-induced breakdown is companioned by the nonlinear optical transformation of initial radiation (diffraction stratification, Cherenkov radiation and interference of its radiation). The chain of corresponding models for various media are represented and discussed. Thus we show that large value for the laser-induced optical breakdown has nonlinear optical processes and therefore this process has complex chain nature this fact must be included for the modeling these processes.*

*Key words: laser-induced optical breakdown, Relaxed Optics, modeling, chain processes, Cherenkov radiation*

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# МОДЕЛЮВАННЯ ПРЯМОГО ЛАЗЕРНО-ІНДУКОВАНОГО ОПТИЧНОГО ПРОБОЮ В ТВЕРДИХ ТІЛАХ

*Задача моделювання лазерно-індукованого оптичного пробою представляється як створення універсального методу для всіх середовищ – від газів до твердого тіла. Це перша спроба детального дослідження цієї проблеми в цілому. Показаний рівень складності цієї проблеми. З фізико-хімічної точки зору оптичний пробій є режимом повного розриву всіх хімічних зв'язків в опромінюється речовині в області лазерного опромінення. У цьому випадку ми можемо визначити поріг руйнування опромінених речовин за допомогою методів релаксаційної оптики. Режим оптичного пробою можна отримати за допомогою трьох способів. Перший – тепловий. У цьому випадку основна релаксація первинних процесів оптичного збудження є теплова. Прикладами цього процесу можуть бути імпульсне мілісекундне та неперервне лазерне опромінення речовини. Другий – плазмовий. В цьому випадку основну роль в оптичному пробої має*

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*формування «колективного» електромагнітного (електронно-іонного) процесу. Прикладами цього процесу є лазерне опромінення імпульсами мілісекундної або наносекундної тривалості. При цьому лазерно-індукована плазма випромінює неперервне випромінювання у всіх напрямках (ефект зірки). Третій – прямий оптичний. У цьому випадку ми маємо пряму багатофотонну іонізацію, і ці процеси носять орієнтаційний характер. Вторинне випромінювання (перевипромінюсвання) це черенковське випромінювання з оптичним збудженням. Цей факт підтверджений експериментальними даними для наносекундного, пікосекундного таі фемтосекундного режимів опромінення. Це відмінність пов'язана з різною природою релаксації первинних оптичних збуджень. Представлено порівняльний аналіз моделювання цих трьох типів процесів. Показано, що третій процес, прямий лазерний пробій, супроводжується нелінійно-оптичними перетвореннями вихідного випромінювання (дифракційна стратифікація, черенковське випромінювання та інтерференція цього випромінювання). Представлено та обговорено ланцюжок відповідних моделей для різних середовищ. Таким чином, показано, що велике значення для лазерного оптичного пробою мають нелінійно-оптичні процеси., Ці процеси мають складну ланцюгову природу і це необхідно враховувати при їх моделюванні.*

*Ключові слова: лазерно-індукований оптичний пробій, релаксаційна оптика, моделювання, ланцюгові процеси, черенковське випромінювання.*

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## МОДЕЛИРОВАНИЕ ПРЯМОГО ЛАЗЕРНО-ИНДУЦИРОВАННОГО ОПТИЧЕСКОГО ПРОБОЯ В ТВЕРДЫХ ТЕЛАХ

*Задача моделирования лазерно-индуцированного оптического пробоя представляется как создание универсального метода для всех сред – от газов до твердого тела. Это первая попытка детального исследования этой проблемы в целом. Показан уровень сложности этой проблемы. С физико-химической точки зрения оптический пробой является режимом полного разрыва всех химических связей в облучаемом веществе в зоне лазерного облучения. В этом случае мы можем определить порог разрушения облученных веществ с помощью методов релаксационной оптики. Этот режим можно получить с помощью трех способов. Первый – тепловой. В этом случае основная релаксация первичных процессов оптического поглощения – тепловая. В качестве примеров таких процессов могут служить импульсное миллисекундное и непрерывное лазерное излучение. Второй – плазменный. В этом случае основную роль при оптическом пробое играет формирование «коллективного» электромагнитного (электронно-ионного) процесса. Примеры этого процесса – лазерное облучение вещества импульсами миллисекундной или наносекундной длительности. В этом случае лазерно-индуцированная плазма излучает непрерывное излучение во всех направлениях (эффект звезды). Третий – прямой оптический. В этом случае мы имеем прямую многофотонную ионизацию и эти процессы имеют ориентационный характер. Вторичное излучение (переизлучение) это черенковское излучение с оптическим возбуждением. Подтверждающие экспериментальные данные получены для наносекундного, пикосекундного и фемтосекундного режимов облучения. Это различие для трех процессов связано с различной природой релаксации первичных оптических возбуждений. Представлен сравнительный анализ моделирования этих процессов. Показано, что третий процесс сопровождается нелинейно-оптическим преобразованием исходного излучения (дифракционная стратификация, черенковское излучение и интерференция этого*

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*излучения). Представлена и обсуждена цепочка соответствующих моделей для различных сред. Таким образом показано, что большое значение для лазерно-индуцированного оптического пробоя имею нелинейно-оптические процессы, и, следовательно, этот процесс имеет сложную цепную природу. Поэтому это необходимо учитывать при моделировании таких процессов.*

*Ключевые слова: лазерно-оптический пробой, релаксационная оптика, моделирование, цепные процессы, черенковское излучение.*

## Problem Statement

Problems of the observation the laser-induced optical breakdown and shock processes in matter as Nonlinear (NLO) and Relaxed (RO) Optical processes are connected with acoustic (thermal) and electromagnetic (plasma and Nonlinear optical) nature [1–4]. These processes may be connected with diffractive stratification of laser beam, self-focusing, self-trapping, generation of supercontinuum radiation (ordered – Cherenkov radiation [3–4], and disorder – plasma radiation) [1–2].

We present this problem from one point of view for all media – from gases to solid [1-4]. Unfortunately the first attempt of observation this problem in main detail in whole are represented in [4] only.

## Analysis of Recent Researches and Publications

According to [1-4], optical breakdown is understood as catastrophic damage caused by strong laser radiation. The cause of optical breakdown is avalanche ionization [1–2]. This process is differed from heat breakdown, which is result of laser-induced heat of irradiated matter, to directoptical multiphotonic ionization. Roughly speaking the optical breakdown is result of rapid introducing energy to matter with laser help. Optical breakdown determine a limit laser intensity of laser radiation, which irradiated matter can absorb.

In whole this problem [1–4] is very complex problem. From physical-chemical point of view the optical breakdown is the regime of fool breakage of all chemical bonds in irradiated matter in zone of laser irradiation [3–4]. In this case we can determine the threshold of breakdown of irradiated matters with help methods of RO (cascade model of excitation the proper chemical bonds in the regime of saturation the excitation) [3–4]. This regime may be received with help three ways. First is thermal. In this case the basic relaxation of first order processes of optical excitation are thermal [2–3]. As example of this process may be continuous laser irradiation of matter in self-absorption range of absorption spectrum. [3–4]. Second is plasma. In this case the main role of the optical breakdown has process of formation "collective" electromagnetic (electron-ionic) process [2–3]. The examples of this process are the irradiation in the millisecond or nanosecond regimes of irradiation [2–3]. In this case laser-induced plasma radiated continuum optical spectra in all direction (star effect) [2]. Third is direct optical [4]. In this case we have direct multiphotonic ionization and these processes have oriental nature [3–4]. The second order irradiation has Cherenkov nature [3–4]. The experimental data were received for nanosecond, picosecond and femtosecond regimes of irradiation [3–4]. This differentiation is connected with various nature of relaxation the first-order optical excitations. Thus we have three ways for the receiving of laser-induced breakdown.

## Purpose of the Study

The comparative analysis of three types modeling is represented. We show that third direct laser-induced breakdown is companioned by the nonlinear optical transformation of initial radiation (diffraction stratification, Cherenkov radiation and interference of its radiation). The chain of corresponding models for various media (solid, liquid and gas) are represented and discussed [3–4].

Thus we show that large value for the laser-induced optical breakdown has nonlinear optical processes and therefore this process has complex chain nature this fact must be included for the modeling these processes [3–4].

## Description of Main Material of Research

### Experimental data

For modeling we select experimental data of complex laser-induced optical breakdown in hexagonal silicon carbide 4H-SiC after irradiation of femtosecond pulses with pulse duration 130 *fs* and wavelength 800 *nm* [5, 6] and in cubic crystals of potassium chloride after irradiation of nanosecond pulses of $CO_2$-laser with pulse duration 30 *ns* and wavelength 10,6 *nm* [7, 8].

Irradiation of silicon carbide crystals had next conditions [5, 6]. Light-penetration direction $\vec{k}$ was perpendicular to electric field $\vec{E}$ of light wave. Samples of 4H-SiC irradiated with help microscope. Focused radiation was incident on a periodic epoxy glue mask with period 20 $\mu m$ [5], which applied to the sample.

Five stages of cascade destruction the irradiated silicon carbide were received [5]. Sectional area of receiving structures was ~ 22 $\mu m$ and the depth of ~ 50 $\mu m$. Samples of silicon carbide were irradiating with two values of energy: 200 *nJ*/pulse and 300 *nJ*/pulse [5, 6]. Optical micrograph of the mechanically thinned sample, which show cross sections of laser-irradiated lines (200 *nJ*/pulse), was representing. Bright-field TEM image of the cross section of a line written with pulse energy of 300 *nJ*/pulse was receiving [5]. These five stages disordered regions were located at a distance from 2 to 4 $\mu m$ apart vertically [5]. Each stage have conic form. Slight misalignment of the tops of the cones observed [5]. Vertical breakdown regions with widths from 150 *nm* to 500 *nm* generated inside these cones [5]. In this case, there are lines in the irradiated nanocavity spherical and ellipsoidal forms with sizes from 10 *nm* to 20 *nm*. Bright-field TEM image of a portion of the cross section of a line was written with a pulse energy of 200 *nJ*/pulse too [6]. Schematic illustrations of the microstructure of a laser modified line and light-propagation direction (k), electric field (E), and scan direction (SD) are showing. Only two groups (groups I and II) of the laser-modified microstructure are selected and drawn [5, 6].

Sectional area of receiving structures was ~ 22 $\mu m$, the depth of ~ 50 $\mu m$. As seen from Fig. 1 (c) we have five stages disordered regions, which are located at a distance from 2 to 4 $\mu m$ apart vertically [5, 6]. Branches themselves in this case have a thickness from 150 to 300 *nm*. In this case there are lines in the irradiated nanocavity spherical diameter of from 10 *nm* to 20 *nm*. In this case irradiated structures have crystallographic symmetry of the initial structure.

In this case diffraction processes may be generated in two stages: 1 – formation of diffraction rings of focused beams [3, 4] and second – formation of diffracting gratings in the time of redistribution of second-order Cherenkov radiation [3, 4]. Second case is analogous to the creation of self-diffraction gratings in NLO, but for Fig. 1 (c) and Fig. 1 (g) our gratings are limited by Much cone of Cherenkov radiation. Roughly speaking only Fig 1 (e) – (g) are represented “clean” breakdown.

Two damages region in a crystal with moderately high density of inclusions were received in [7] for crystals *KCl* after irradiation by $CO_2$-lase pulses (wavelength 10,6 $\mu m$, duration of pulse 30 *ns*). The laser was known to be operating in the lowest-order transverse Gaussian mode. There were several longitudinal modes, however, which contributed a time structure to the pulse, periodic at the cavity round-trip time. The phase relationships between the longitudinal modes varied from shot to shot, changing the details of the time structure and causing the peak of the envelope to fluctuate by ±15% [7]. Energy of irradiation had value 2 *J*/pulse [8].

Successive laser shot (1/sec) was focusing into bulk single crystals using a 1–inch focal length "Irtran 2" lens [7].

According to [7] these results show that spatial laser-induced heterogeneities are result of influence inclusions. The damage bubbles occur randomly near, not necessarily in, the tiny focal volume. At a well-defined power threshold, an elongated pointed bubble forms, its vertex falling at the focus [Fig. 2(b)]. This power level is regarded ass the bulk intrinsic breakdown threshold. Its value is reproducible in crystals from different manufacturers, with inclusions or without. When no inclusion-free samples of a compound were available, the considerations mentioned above were using to determine the dielectric strength [7].

**Modeling and discussions**

The first laser-induced filaments were received in the liquid [1, 3]. Later researches shown that analogous phenomena are characterized the solid and gas too [1, 3, 4]. Strongly speaking, these filaments are sparks of optical breakdown.

More universal concept is physical-chemical [3, 4]. According to this concept the critical value of power $P_{cr}$ for the self-focusing may be determined in next way. Volume density of energy of the creation self-focusing process may be determined with help next formula $W_{crvol}$ [1, 3, 4]

$$W_{crvol} = E_a N_{nc}, \quad (1)$$

where $E_a$ – energy of activation corresponding "nonlinear" centers; $N_{nc}$ – their concentration.

Surface density for optical thin may be determined as [3, 4]

$$W_{crsur} = W_{crvol} / \alpha, \quad (2)$$

where $\alpha$ – absorbance index. Integral value of energy may be determined as [3–4]

$$W_{crin} = W_{crsur} \cdot S, \quad (3)$$

where $S$ – the square of irradiation.

In this case [3–4]

$$P_{cr} = W_{crin} / \tau_{ir}, \quad (4)$$

where $\tau_{ir}$ is duration of laser irradiation.

The determination the concentration of scattering centers must be determined with conditions of corresponding experiment. It is determined by the conditions of observation the proper phenomena.

Next step of determination the density of energy in our cascade is condition of diffractive stratification. This condition may be determined with help of sizes the diffractive rings. We can estimate density of energy in plane of creation the diffractive stratification for $n$=5.

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Conic part of filament radiation has continuum spectrum: from ultraviolet to infrared. At first this effect was called superbroadening. Therefore it may be interpreted as laser-induced Cherenkov radiation [3, 4]. The angle 2θ in the vertex of an angle [3-5]. is double Cherenkov angle. In this case we have frozen picture of laser-induced destruction of 4H-*SiC* with help Cherenkov radiation [3, 4].

For the modeling of the Cherenkov radiation we used two models: Golub macroscopic model and modified Niels and Aage Bohrs microscopic model [3, 4].

First, macroscopic may be represented according by Golub [3, 4]. The similarity between charge particle and light-induced Cherenkov radiation one can invoke the analogy between Snell's law and Cherenkov radiation [3, 4]. This natural since both effects can be derived in the same way from the Huygens interference principle. In [3, 4] the point of intersection of a light pulse impinging at an angle $\varphi$ on a boundary between two media moves with velocity $V = C / n_1 \cos\varphi$. As Golub shown that this relation, which can be obtained from Snell's law, gives the Cherenkov relation [3–4].

$$\cos\theta = C / n_2(\omega) V, \tag{5}$$

where $n_2(\omega)$ – the nonlinear refraction rate [3–4].

This formula allows explain the angle differences for various type of Cherenkov radiation. In this case *V* may be represented as velocity of generation the optical-induced polarization too [3, 4].

The microscopic mechanism of laser-induced Cherenkov radiation is expansion and application of Niels and Aage Bohrs microscopic theory of Cherenkov radiation as part of deceleration radiation on optical case [3, 4]. For optical case the Bohrs hyperboloid must be changed on Gaussian distribution of light for mode $TEM_{00}$ or distribution for focused light of laser beam [3, 4]. In this case Cherenkov angle may be determined from next formula

$$\theta_{Ch} + \alpha_{ir} = \pi/2 \text{ or } \theta_{Ch} = \pi/2 - \alpha_{ir}, \tag{6}$$

where $\alpha_{ir}$ – angle between tangent line and direction of laser beam.

Angle $\alpha_{ir}$ was determined from next formula [3–4]

$$\tan\alpha_{ir} = d_b / l_{sf}, \tag{7}$$

where $d_b$ – diameter of laser beam, (7 mm), $l_{sf}$ – length of focusing or self-focusing. In our case $\alpha_{ir}$ is angle of focusing or self-focusing.

This formula is approximate for average angle $\alpha_{ir}$.

The Golub formula (5) was used for the determination product $n_2(\omega)V_{nl\ pol}$ [3, 4]. Self –focusing and Cherenkov angles and product $n_2(\omega)V$ were estimated for *LiF*, $CaF_2$, fused silica, water and glass BK-7 in [4]. Thereby microscopic modified Bohrs theory and macroscopic Golub model are mutually complementary methods [3, 4].

The decreasing of Cherenkov angle and product $n_2(\omega)V$ for increasing of laser radiation intensity are corresponded to increasing of nonlinear refractive index and decreasing the speed of polarization (multiphotonic and multiwave processes) [3, 4].

In whole, microscopic mechanism of laser-induced Cherenkov radiation may be represented as nonequilibrium spectrum of all possible Nonlinear Optical phenomena in the local points of propagation the laser beam [3, 4].

The estimation of sizes the cascade of volume destructions in [5] was explained with help modified models of Rayleygh rings [3, 4].

The distance between diffraction spots and proper moving foci was determined with help next formula [3–4]:

$$l_{nf} = \frac{d_{ndif}}{2\tan \varphi/2}. \quad (8)$$

Qualitative explanation of development of cascade the destructions was next. The focus of each diffraction zone (spot) is the founder proper shock optical breakdown. But foci with more high number are placed in the “zone” of influence of previous foci. Therefore only first stage from fives [5] is represented pure shock mechanism (Mach cone). Mach cones are characterized the second and third stages from five [5]. But its maximums are displaced from center. It may be result if interaction second and third shock waves with previous shock waves: first – for second wave and first and second for third waves. The chock mechanism of destruction certifies a linear direction of optical breakdown. This direction is parallel to direction of shock wave and radiated spectrum is continuum as for Cherenkov radiation and as for observed laser-induced filaments in water and air [3, 4]. Thus, basic creator of optical breakdown traces is secondary Cherenkov radiation and shock waves. This radiation is absorbed more effectively as laser radiation and therefore the creation of optical breakdown traces is more effectively as for initial laser radiation. Cherenkov radiation is laid in self-absorption range of 4H-*SiC*, but 800 *nm* radiation – in intrinsic range [3, 4]. For the testing of this hypothesis, we must measure the spectrum of secondary radiation. In this case, we can use physical-chemical cascade model of excitation the proper chemical bonds of irradiated matter in the regime of saturation the excitation.

The conclusion about diffractive stratification of focused radiation may be certified by experimental data, which are represented in [5 – 7].

We can rough estimate basic peculiarities of energy distribution in Mach cone in five stages of laser-induced destruction of cascade through next formula [3, 4]

$$E_{1ob} = \frac{\pi^2}{4}\left(\sum_{i=1}^{5} n_{iav}^2 l_{iav}\right) r^2 N_{aSiC} E_{Zth}, \quad (9)$$

where $n_{iav}$– average visible number of filaments in proper group of cascade, $l_{iav}$=1000 *nm* – average length of filaments in proper group of cascade, $r$ = 10 *nm* – average radius of filament, $N_a$ – atom density of 4H-*SiC*, $N_{aSiC} = 9,4 \cdot 10^{21}\ cm^{-3}$ – the atomic density of 4H-*SiC*.

For further estimation we use next approximation $n_{1av} = n_{2av} = n_{3av} = n_{4av} = n_{5av} = 100$, [3, 4].

Energy, which is necessary for the optical breakdown our nanotubes may be determined in next way. Zeitz threshold energy for 4H-*SiC* is equaled $E_{Zth}$ ~ 25 *eV* [3, 4]. Let

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this value is corresponded to energy of optical breakdown. Therefore, summary energy $E_{1ob}$ is equaled

$$E_{1ob} = N_{asnt} \cdot E_{Zth} = 23,2\ nJ. \tag{10}$$

This value is equaled of ~ 8% from pulse energy or ~ 30% from the effective absorbed energy of pulse. In this case we have more high efficiency of transformation initial radiation to «irreversible» part of Cherenkov radiation. It is result of more intensive excitation comparatively with classical methods of receiving the Cherenkov radiation. In this case we have pure photochemical processes. The experimental data for intrinsic absorption (Fig. 5) show that for short pulse regime of irradiation (femtosecond regime) basic processes of destruction the fused silica and calcium fluoride are photochemical (multiphoton absorption in the regime of saturation the excitation). But basic peculiarity of experimental data Fig. 5 is transformation the initial laser radiation (wavelength 800 *nm*) to continuum Cherenkov radiation. From length of optical breakdown in 4H-SiC we can determine average absorption index of Cherenkov radiation. It is ~ $10^4$ $cm^{-1}$. This value is corresponded to violet-blue range of absorption spectrum of 4H-*SiC* [3, 4].

Correlation between energy of optical breakdown and threshold energy of self-focusing for 4H-*SiC* is equaled 78333 and 117500 [3, 4].

Concept of diffractive stratification allows explaining the surface character of Cherenkov radiation. This radiation is generated in the region of corresponding focused diffractive ring [3, 4].

For the estimations the sizes and forms of nanovoid we used modified Raylegh model [3–4]. Maximal radius of nanovoids is determined as

$$R_{\max} = \frac{2R}{0{,}915r}\sqrt{\frac{E_{ir}}{\pi\tau_i cE}}, \tag{11}$$

where $T_c$ – the time of creation the nanovoid (bubble), $R$ is radius of nanovoid, $r$ – radius of irradiated zone, $E$ – Young module, $E_{ir}$ – energy of one pulse. $\tau_i$ – duration of pulse, $c$ – speed of light [3–4].

If we substitute $r$ = 250 *nm*, $R$ = 10 *nm*, $E$=600 *GPa* [3–4], $E_{ir}$=130 *nJ*, $\tau_i$ = 130 *ps*, $c$=3·$10^8$ *m/s*, than have $R_{\max}$=11 *nm*. Experimental values for 4H-*SiC* 8 – 10 *nm* [3–4].

Form of nanovoids was determined as ratio $\alpha$ between longitudinal $\vartheta_{ls}$ and transversal $\vartheta_{ts}$ speed of sound [3–4]

$$\alpha = \frac{\vartheta_{ts}}{\vartheta_{ls}} = \sqrt{\frac{(1-2\nu)}{2(1-\nu)}}. \tag{12}$$

Where $\nu$ – Poisson's ratio [4].

But this ratio must be true for shock waves too. Therefore for silicon carbide for $\nu$ = 0,45 [3, 4] $\alpha$ = 0,33. Roughly speaking last ratio is determined the step of ellipsoidal forms of our nanovoids [6].

In [3–4] we are estimated maximal longitudinal and transversal $R_{\max i}, i \in (l,t)$. These values are 6 *nm* and 19 *nm* properly.

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In this case we represented 4H-SiC as isotropic plastic body. For real picture we must represent hexagonal structure. But for the qualitative explanation of experimental data of [5, 6] this modified Rayleygh model allow explaining and estimating the sizes and forms of receiving nanovoids [3–4].

Now we used physical-chemical method of estimation for the modeling experimental data for *KCl* [7]. Density of atoms of *KCl* is equaled $3{,}1\cdot 10^{22}\ cm^{-3}$. Zeits energy for KCl has value ~ 30 *eV* [3].

Results of this modeling are represented in Table 1.

Table 1

Basic characteristics for laser-induced optical breakdown for *KCl* [7]

| Figure | $d_{average}$, $\mu m$ | $l$, $mm$ | $V_{ob}$, $10^{-7}\ cm^{-7}$ | $N_{ob}$, $10^{15}$ | $E_{KClob}$, $10^{-2}\ J$ |
|---|---|---|---|---|---|
| Fig. 2(a) | 0,5 | 2 | 1,57 | 4,87 | 2,32 |
| Fig. 2(b) | 0,5 | 3 | 2,36 | 7,31 | 3,48 |

We used next approximations. Photography, which used in [7], gives a blurry image compared to the bright-field TEM image, which are used in [5, 6]. Therefore, we can't see the microstructure of optical breakdown for *KCl*. In this case we use rough average approximations for diameter $d_{average}$ and length $l$ of cascade laser-induced optical breakdown for results [7]. Volume of cascade may be determined as cylinder volume.

Experimental data of [7] are similar to experimental data of [5, 6]. But regimes of irradiation of [7] are similar to mode $TEM_{01}$. Therefore, we have two channels of generation the cascade of laser-induced optical breakdown.

The distances between neighboring bubbles of [7] are more as between regions of destruction in [5]. But conditions of focusing the radiation in these both cases are equivalence. Therefore, the distances between neighboring bubbles $l_2$ ([7])and neighboring regions of destruction $l_1$ ([5]) are connected by next formula, which is received with help formula (8)

$$l_2 = \frac{d_{ndif\,2} \tan\left(\varphi_1/2\right)}{d_{ndif\,2} \tan\left(\varphi_2/2\right)} l_1 = \frac{\lambda_2 \tan\left(\varphi_1/2\right)}{\lambda_2 \tan\left(\varphi_2/2\right)} l_1. \tag{13}$$

In whole, the correlation of these distances is depended from wavelength of irradiation and focusing angles, including intensity of irradiation? Which is determined the step o f homogeneity of irradiated matter. If we substitute in formula (13) $\lambda_2 = 10,6\,\mu m$ and $\lambda_1 = 0,8\,\mu m$ and $\varphi_1 = \varphi_2$ then we'll receive

$$l_2 = 13,25\, l_1. \tag{14 a}$$

Energy characteristics of irradiation weren't represented in [7] but were reference on [8]. Therefore, we select value 2 *J*/*pulse* from [8]. In this case we have effective using energy. Methods of estimations of energy characteristics of Table 1 are rougher as for 4H-*SiC*. But we must suppose that focused laser irradiation has diffraction stratification, generation of Cherenkov radiation and interference of this Cherenkov radiation. On second regime of irradiation in [7] we see 5-7 steps of cascade optical breakdown. Sources of Cherenkov radiation are diffraction-stratified cones.

If this scenario is true, we have as for 4H-SiC effective transformation the energy of laser radiation to cascade of laser-induced breakdown for *KCl* too. This value is 11,6 – 17,4 percents.

Experimental data, which are represented in [5, 6] and [7], are similar to bead lightning [3] and resembles a frozen picture in a travelling wave lamp. But for the formation these processes we must have two electrodes and modulated external field. For the case of laser-induced breakdown, we have only laser field, its nonlinear transformation, including diffractive stratification of laser beam, a generation of Cherenkov radiation and its interference, and multiphotonic absorption. In this case, we have internal nonlinear and relaxed optical processes.

As we see basic mechanism the heterogeneities cascade damages of laser-induced optical breakdown is nonlinear optical transformation of initial radiation. Inclusions in 4H-*SiC* and *KCl* are distributed homogenously and therefore one can't be the source of laser-induced heterogeneities. Potassium chloride crystals are obtained from an aqueous solution, and this method allows you to obtain the most pure crystals in comparison with other methods (Kyropoulos, Bridgman-Stockbarger, zone melting, etc.).

## Conclusions

1. Comparative analysis of basic three types models of laser-induced optical breakdown in matter is representing.
2. Basic peculiarities of modeling the direct laser-induced optical breakdown are discussing.
3. The experimental data of laser-induced breakdown in 4H-*SiC* and *KCl* are analyzed.
4. Complex cascade model for explanation the direct laser-induced optical breakdown is representing.
5. The influences of diffraction stratification, Cherenkov radiation and interference of its Cherenkov radiation on laser-induced optical breakdown are showing.
6. Basic cause of receiving laser-induced heterogeneities is nonlinear and relaxed optical transformations of laser radiation.

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